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DURABLE AND HIGH STRENGTH CONCRETE WITH 40% OR MORE FLY ASH IN PLACE OF CEMENT

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Innovative Housing Grants Program

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DURABLE AND HIGH STRENGTH CONCRETE WITH 40% OR MORE FLY ASH IN PLACE OF CEMENT

May 1991

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The views and conclusions expressed and the recommendations made in this report are entirely those of the authors and should not be construed as expressing the opinions of Alberta Municipal Affairs.

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FOREWORD

The project documented in this report received funding under the Innovative Housing Grants Program of Alberta Municipal Affairs. The Innovative Housing Grants Program is intended to encourage and assist housing research and development which will reduce housing costs, improve the quality and performance of dwelling units and subdivisions, or increase the long term viability and competitiveness of Alberta's housing industry.

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As the type of project and level of resources vary from applicant to applicant, the resulting documents are also varied. Comments and suggestions on this report are welcome. Please send comments or requests for further information to:

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Mr. M. Akkad-Salam conducted almost all the experiments. Dr. Harsha Wijeweera scheduled and supported the experimental work. Although the skeleton of the report was prepared by the first author, Mr. M. Akkad-Salam, Dr. Wijeweera, and Mr. Gopal Achari filled in the details as directed. Further fundamental work (which was not part of this project) is in progress to evaluate the sources of strength and durability development in high fly ash concrete. Mr. Akkad-Salam will write his M.Sc. thesis on this project plus the additional work.

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EXECUTIVE SUMMARY

The fundamental objective of this research project was to develop optimum design mixes for durable high strength concrete, with considerable economic benefits, by incorporating high amounts of fly ash replacing cement. The fly ashes studied in this project were those produced from the coal burning power plants located in Sundance, Wabamun, and Forestburg in Alberta. The fly ashes were sub-bituminous Class C type, meeting the requirements of ASTM C-618 classification, except for Wabamun which is available as raw ash.

The research work for this project was carried out in three phases. Phase I consisted of an extensive search and review of the literature related to producing and testing high fly ash high strength concrete. In phase II a detailed experimental program was executed to produce durable high strength concrete mixes containing high amounts of fly ash. This included testing 70 trial mixes in order to achieve optimum mix proportions for the final design mixes. An economic analysis was done in phase III to assess the feasibility of using large amounts of fly ash in concrete. The suitability of such mixes for specific applications was also investigated.

The literature indicates that introducing fly ash into concrete will improve characteristics of the mix in the following ways. In the case of fresh concrete, the result is better workability, reduced segregation and bleeding, and reduced temperature rise due to hydration. In the case of hardened concrete, the result is equal or higher strength after some time, lower permeability, lower drying shrinkage and higher resistance to sulphate attack. Furthermore, partial replacement of cement by fly ash also reduces construction costs. Longer setting time and lower rate of strength development have been identified, in the literature, as the main disadvantages of using large amounts of fly ash in concrete.

The literature indicates that high fly ash concrete with high initial strength and workability can be used in the construction of structural elements such as floor slabs, beams and columns. Furthermore, concrete containing high amounts of fly ash and proper chemical admixtures could also be used in paving roadways and driveways of

residential buildings. However, very little research has been directed in the past to developing high fly ash mixes capable of producing high strength durable concrete. So far, Alberta fly ash has not been used for producing such mixes.

The main types of concrete design mixes produced in this study are:

- 40%, 50%, and 60% replacement of cement by Sundance fly ash,
- 40%, 50%, and 60% replacement of cement by Forestburg fly ash,
- 40%, 50%, and 60% replacement of cement by Wabamun fly ash, and
- 50% Sundance fly ash and 50% high early strength cement.

The optimum mix proportions were determined based on the test results from a series of trial mixes. The factors that were varied in the trial mixes include the cementitious material content, aggregate proportions, water cement ratio, and the amounts of air-entraining agent, superplasticizer, and set accelerator.

Results from the experimental and economic analysis of this study reveal that high amounts of Alberta fly ash can be used to develop low cost high strength durable concrete mixes. The following conclusions can be made about the high fly ash concrete mixes designed in this program:

1. High workability results from the introduction of fly ash.
2. There is an increased demand for air-entraining agent compared to mixes with no fly ash.
3. Longer setting times are required; typically 3 to 6 hours longer than conventional concrete.
4. High compressive strengths, exceeding 45 MPa at 28 days, can be achieved.
5. Durability in freeze-thaw action is adequate.
6. Resistance to sulphate attack is excellent.
7. Construction costs, due to the lower cost of fly ash compared to that of cement, can be reduced.

In general, high fly ash concrete with proper chemical admixtures can be designed to be as strong and durable as regular high strength concrete. Such high fly ash high strength concretes cost less than regular concrete.

1. INTRODUCTION

1.1 General

Fly ash is a waste by-product generated by coal burning power plants. Over the years many innovative uses of fly ash have been developed; but, in Canada only about 10% to 20% of the total ash produced is currently utilized. Most fly ash use is in the cement and concrete industry.

The properties of fly ash are extremely variable and depend upon several factors such as the type and origin of coal, degree of pulverization, method of collection and storage, firing temperature and oxidation condition. Fly ashes from Western Canada are mostly sub-bituminous Class C type, while those from Eastern Canada are bituminous Class F type. Class C and Class F fly ashes possess various physical and chemical properties similar to that of a pozzolan. A pozzolan is a siliceous or siliceous and aluminous material which in itself possesses little or no cementitious properties but in the presence of moisture will react with lime to form compounds possessing cementitious properties. In addition to their pozzolanic behaviour, Class C fly ashes exhibit self-hardening properties.

1.2 Purpose of the study

The usual practice being adopted so far is to replace no more than 20% to 30% of cement with fly ash in structural concrete. This study was conducted to determine whether 50% or more of sub-bituminous Alberta fly ash could be used to develop high strength and durable concrete. Although higher cement replacement levels are possible, very little research has been directed in the past towards developing high fly ash mixes capable of producing high strength durable concrete. The very few studies that were conducted on the use of high cement replacements were for fly ashes different in origin to those examined in this study.

By using large amounts of fly ash, a relatively cheap waste material, in mix designs lower concrete prices can be achieved. At the same time, this will result in overcoming the problem and cost of the ultimate disposal of fly ash. Furthermore, high fly ash concrete also has the potential of being a highly durable material, as revealed in the available literature. It is also reported that these types of concrete mixes can be used in the construction of driveways and sidewalks in addition to their use in structural elements such as slabs, beams, columns, foundations, etc.

1.3 Particular Aspects that Need Investigation

So far very few studies have been done with respect to the utilization of large amounts of fly ash in producing high strength concrete mixes for the construction industry. However, no literature is available that indicates the use of Alberta fly ashes in developing such mixes. This study analyses and assesses the feasibility of producing economically viable high strength durable concrete mixes by replacing 40% or more of the cement with Alberta fly ash. Three types of Alberta fly ashes, namely, Sundance, Forestburg, and Wabamun are investigated in this research.

Previous studies indicate that use of high amounts of fly ash in concrete may have the following adverse effects on the properties of the mix.

- significantly longer setting times (in some cases a delay in the initial setting time by more than 14 hours),
- lower initial strength development rates.

This investigation attempts to improve on the above inherent characteristics of high fly ash concrete by the use of proper chemical admixtures.

1.4 Scope and Focus of the Study

As outlined in Section 1.3, this study focuses its attention on using Alberta fly ash in developing high strength durable concrete. The designed mixes should possess the following characteristics:

- compressive strengths in the range of 45 to 60 MPa at 28 days,
- high workability close to or in excess of 100 mm,
- short setting times and high early strength development comparable to that of concrete without fly ash,
- low water cement ratio to achieve high strengths, and
- air content of around 6% in order to achieve freeze-thaw durability.

The main types of concrete design mixes that were considered are:

- 40%, 50%, and 60% replacement of cement by Sundance fly ash,
- 40%, 50%, and 60% replacement of cement by Forestburg fly ash,
- 40%, 50%, and 60% replacement of cement by Wabamun fly ash, and
- 50% Sundance fly ash and 50% high-early-strength cement.

Although initially study of mixes with only 50% and 60% fly ash replacement of cement was proposed, the test program was expanded to cover 40% fly ash replacement.

Two control mixes, one with normal portland cement (Type I) and the other with high early strength cement (Type III) were also considered for comparative purposes.

To reach the optimum design for all of the above mentioned types of mixes, up to seventy trial mixes were performed in the laboratory. The following factors were varied to test their effect on properties of fresh and hardened concrete;

- cementitious material content,
- aggregate proportion,
- water-cement ratio,
- air-entraining agent,
- superplasticizer, and
- set accelerator.

The properties monitored were;

- workability,
- air entrainment,
- initial and final setting times,
- compressive strength and
- freeze-thaw durability.

The designed mixes were evaluated to ensure they are economically feasible for use in the construction industry.

1.5 General Layout of the Report

This report is composed of five ensuing chapters structured as follows;

Chapter 2: Fly Ash and Its Properties (discusses different properties of fly ash including fineness or specific surface area, specific gravity, mineralogy, chemical composition, and reactivity).

Chapter 3: Use of Fly Ash in Concrete (description of the use of high amounts of fly ash in concrete and the properties of fresh and hardened concrete that are influenced by this).

Chapter 4: Experimental Program (description of the materials used and the different testing methods inherent in this research program).

Chapter 5: Results and Discussions (description of the experimental program along with an economic evaluation of the design mixes).

Chapter 6: Conclusions.

2. FLY ASH AND ITS PROPERTIES

2.1 General

Fly ash is a by-product of the combustion of pulverized coal in thermal power plants and is removed by mechanical collectors and/or electrostatic precipitators as fine residue from the combustion gases. Fly ash accounts for about 75% to 85% of coal ash produced by suspension fired furnaces. The remainder is collected as bottom ash or boiler slag.

With increasing demand for energy and a diminishing supply of oil, the use of coal in power generation is growing rapidly. In Canada, more than 3 million tonnes of fly ash are produced annually. Alberta accounts for 60 to 70 percent of total ash production in Canada. Only about 20% of this ash is currently being used, the rest being disposed of at substantial cost to the utility industry and, therefore, the consumer.

Understanding the physical and chemical properties of fly ash is of great importance when assessing their effects on concrete properties. This chapter briefly outlines the above properties indicating their effect on the pozzolanic behaviour of fly ash.

2.2 Physical Properties

The physical properties of fly ash are very variable depending on the coal source, fineness of the grinding of the coal prior to combustion, additives mixed with coal for pollution control, and the method of collection. The different physical properties of fly ash investigated include the specific surface area and fineness, specific gravity, crystallinity and texture, and mineralogy.

2.2.1 Specific Surface Area and Fineness

Fly Ash is made up of very small spherical particles collected from combustion chambers in power plants by electrostatic precipitators or mechanical precipitators. Most of the fly ash particles are made up of clear glass spheres and spongy particles. The clear glass spheres are smaller than other particles and as a result have a high specific surface area while the spongy particles are larger and generally of low specific surface area (Watt and Thorne, 1965). The small particles result in the high specific surface area of fly ash as determined by different standard tests including Blaine air permeability, single point B.E.T nitrogen sorption method, etc. Sixty percent of the particles in the ash, numerically, have diameters less than 3μ, however these particles only contribute less than 10% of the total weight (Watt and Thorne, 1965). The specific surface area ranges from 2000 to 6000 cm^2/g (Davis, 1937).

Joshi and Marsh (1987) determined the specific surface area of fourteen fly ashes from different power plants across Canada by the Blaine air permeability and the single point B.E.T nitrogen sorption method. The specific surface area values for the different fly ashes are presented in Table 2.1 (taken from Joshi and Marsh, 1987). The results showed that ash collected by electrostatic precipitators had, for the most part, higher specific surface area values compared to those collected by mechanical precipitators. Data from the two separate tests showed considerable variation in the specific surface area values. The higher specific surface area values measured by the nitrogen sorption method are due to the presence of high surface area particles of unburnt carbon. Such high surface area carbon particles did not influence the air permeability test results.

Table 2.1 Specific Surface Area of 14 Canadian Fly Ashes.

Fly Ash No.	Coal Type	Source	Overall Apparent Specific Gravity	% Retained on 45 μm Sieve	Specific Surface Area (m^2/g)	
					Air permeability	B.E.T Method
1	Sub-Bituminous	Alberta	2.19	32.0	0.42	1.52
2	Sub-Bituminous	Alberta	1.92	26.0	0.46	1.61
3	Sub-Bituminous	Alberta	1.91	22.0	0.43	1.61
4	Sub-Bituminous	Alberta	2.03	9.8	0.59	1.64
5	Lignite	Saskatchewan	2.54	2.8	0.50	1.14
6	Sub-Bituminous	Saskatchewan	2.15	20.4	0.22	6.70
7	Lignite	Saskatchewan	2.37	44.8	0.17	1.01
8	Lignite	Saskatchewan	2.39	26.6	0.22	3.47
9	Bituminous	Ontario	2.46	24.0	0.28	0.55
10	Bituminous	Ontario	2.31	27.0	0.25	3.28
11	Bituminous	New Brunswick	2.94	21.4	0.31	2.68
12	Bituminous	New Brunswick	2.87	26.4	0.18	0.43
13	Bituminous	Nova Scotia	2.53	28.2	0.36	0.85
14	Sub-Bituminous	Nova Scotia	2.44	34.2	0.38	0.67

average difference	1.10 m^2/g
standard deviation of mean of 14 readings	1.44 m^2/g

2.2.2 Specific Gravity

The specific gravity of fly ash varies significantly for particles of different shapes, color, and chemical composition (Watt and Thorne, 1965). The specific gravity ranges from 1.3 for irregularly-shaped black coal particles which contain few mineral grains, up to 4.8 for spherical and rounded light brown to black particles that contain 50% to 95% of the total iron present in fly ash (Abdun Nur, 1961). Joshi and

Marsh (1987) investigated the specific gravity of the fourteen Canadian fly ashes mentioned in the previous section. Their values ranged from 1.91 for ash No. 3 up to 2.94 for ash No. 11 (Table 2.1). The proportion of particles of low specific gravity was determined from the amount of ash found to float on liquids of different densities. The majority of the light particles were coarse and could be easily discerned by the naked eye. Fly ash particles are generally lighter in weight than cement particles which have typical specific gravity values of around 3.1.

2.2.3 Mineralogy

Fly ash contains 11% to 48% crystalline matter, the rest being amorphous material and carbon particles. The amorphous portion consists of siliceous, aluminous and ferruginous glasses. The four major crystalline phases include; Quartz, Mullite, Haematite, and Magnetite. These phases can be detected by microscopic examination using a scanning electron microscope or by X-ray diffraction or energy dispersive X-ray. Watt and Thorne (1965) analyzed, mineralogically, seven fly ashes using X-ray methods. They found out that the total content of crystalline matter (Table 2.2) was between 11 and 27%, and the glass content ranged between 71 and 88%.

Joshi et al. (1975) conducted scanning electron microscopy studies to examine morphology of hydrated and unhydrated fly ash samples. Results indicated that most of the reactive portion of the ash is on the particle's surface. Also, as the fly ash particle size increases, the amount of crystalline SiO_2 increases and the quantity of calcium containing compounds decreases. It is reported that SiO_2 does not take part in self hardening reactions but does contribute to pozzolanic reactions. It is found that 95% of the mineral matter in coal is composed of Kaolinite, Pyrite, and Calcite.

Table 2.2 Mineralogical Analysis of Fly Ashes*.

Fly Ash	Quartz (%)	Mullite (%)	Haematite (%)	Magnetite (%)	Carbon** (%)	Glass (%)
Dunston	4.5	11	2.7	1.4	3.1	77
Dunston	3.8	11	1.9	1.2	2.0	80
Ferrybridge	2.8	6.5	1.6	1.9	1.5	86
Ferrybridge	2.2	6.5	1.1	0.8	0.9	88
Hams Hall	3.5	10	1.6	1.2	0.6	83
Rye Hall	8.5	14	2.1	2.5	2.4	71
Skelton Grange	4.1	10	2.4	2.6	2.1	79

* Taken from Watt & Thorne (1965)

** Determined chemically

2.3 Chemical Composition

Fly ashes from sub-bituminous and lignite coals are characterized by a relatively high proportion of calcium oxide (CaO) and magnesium oxide (MgO) as distinct from bituminous coals which are usually low in CaO and MgO, and relatively high in ferric oxide (Fe_2O_3) content. The amount of unburned coal in ashes varies depending on the rate of combustion, air/fuel ratio, and the degree of pulverization of the coal (Berry and Malhotra, 1987). In general, fly ash from sub-bituminous coals contains very little unburned carbon. Plants that operate only intermittently, burning bituminous coals, produce the largest percentage of unburned carbon. Fly ashes from Alberta, Saskatchewan and Manitoba are derived from sub-bituminous and lignite coals. Fly ashes produced in the Eastern provinces are derived from bituminous coals. The chemical properties of some Canadian fly ashes are given in Table 2.3.

Silica and Alumina make up the main constituents of fly ash. These compounds are present mainly in a glassy form. Baker et al. (1978) obtained elemental ratios of Al, Si, and Fe by determining the ratios of X-ray peak intensities. The results demonstrated that these ratios are fairly constant with particle size, for a given density range, indicating that the matrix composition is not a function of particle size.

Table 2.3 Chemical Composition of Different Ashes*.

Fly Ash	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (total %)	MgO (%)	SO_3 (%)	LOI** (%)	NaO (%)	K_2O (%)
Forestburg	55.20	20.69	6.15	8.89	1.17	0.42	0.22	4.15	1.00
Sundance	57.10	23.59	3.40	10.59	2.11	0.26	2.34	0.30	0.50
Wabamun	59.22	22.25	3.59	10.60	0.65	0.20	0.42	0.54	0.90
Laramie	38.14	20.74	5.23	23.94	4.58	1.90	0.42	1.42	0.42
Nanticoke	49.17	23.32	11.81	5.52	0.65	0.85	5.67	0.54	0.90
Boundary Dam	45.20	21.00	3.40	12.40	3.11	0.70	2.05	2.90	--
Lingan	44.70	18.00	19.20	0.80	0.80	1.00	6.25	0.40	2.93
Inert+	99.80	--	--	--	--	--	0.10	--	--
Limestone^x	0.70	--	--	55.10	0.40	--	0.20	--	--

* taken from Langan et al. (1989)

** LOI : Loss-on-ignition

+ all other components less than 0.1%.

x CO_2 content = 43.2%.

2.4 Reactivity

Fly ashes exhibit pozzolanic activity. The metastable alumino silicates present in fly ashes react with calcium ions in the presence of moisture to form water insoluble cementitious calcium silicate and aluminate hydrates. Because of this pozzolanic property, fly ash can be utilized in many construction materials. In addition to their pozzolanic property, sub-bituminous and lignite fly ashes also possess some self-hardening properties. The self-hardening effect seems to be related to the presence of free lime. Most of the Alberta fly ashes, basically being sub-bituminous, exhibit varying degrees of this self-hardening property.

The reactivity of fly ash is dependent on many parameters, most important of which are loss-on-ignition or carbon content, specific surface area or fineness, and chemical composition.

The effect of fineness on the pozzolanic activity can be related to the fraction retained on a 45 μm sieve and to the specific surface area of fly ash (Sherwood and Ryley, 1966). Watt and Thorne (1965) studied the effect of particle size on pozzolanic characteristics by passing finely ground minerals through coal-gas-flame to produce synthetic fly ashes. They observed that the activity was determined predominantly by the specific surface area and was independent of the composition of the particles. It was noticed that chemical methods of assessment of pozzolanic activity correlated well with crushing strengths of the mortars at periods of up to 182 days. Joshi and Rosauer (1973) studied the effect of fineness, crystallinity, and chemical composition on the pozzolanic activity of synthetic fly ash. The study showed an opposing view that the surface area contributed less to the development of pozzolanic strength of lime-ash mortars than the amount of glassy phase present. It was observed that the rate of strength gain decreased proportionally with an increase in specific surface area. Many investigators and industrial users of fly ash state that when fly ash is ground, pozzolanic activity increases significantly (Joshi, 1970).

The pozzolanic activity of fly ash also depends on the mineralogy of the material. The pozzolanic activity of an ash resides principally in the glassy particles which are formed from the clay minerals originally present in the coal (Watt and Thorne, 1965). The glassy or non-crystalline structure of fly ash is derived from rapid quenching from high temperatures (Joshi, 1979).

Chemical composition of fly ash has a marked effect on its pozzolanic activity, especially depending on the calcium oxide and carbon content. Pozzolanic activity of fly ash is directly related to the amount of calcium oxide present (Joshi, 1978). Thus, sub-bituminous Class C fly ashes with high contents of free lime exhibit self hardening properties as well as good pozzolanic activity. Another chemical component in fly ash that has considerable impact on the pozzolanic activity is carbon. Carbon tends to predominate in size fractions larger than 44 μm (Watt and Thorne, 1965). The carbon content, as determined by a standard loss-on-ignition test, has an adverse effect on the pozzolanic activity of fly ash mixes. Carbon also acts as a diluent of the active pozzolanic matter in fly ash. Thus, as a result of its undesirable effects, different organizations specifying the use of fly ash as a pozzolan limit the carbon content or loss-on-ignition in fly ashes from 5% to 12% (Joshi, 1979).

Another factor affecting the pozzolanic activity of fly ash could be iron oxide. Iron was found to reduce the pozzolanic activity of fly ash. However, investigations performed by Davis (1937) suggest that fly ashes which have moderate amounts of alumina and iron oxide are superior in reactivity to those containing a high amount of silica.

2.5 Types of Fly Ash

ASTM Standard #618 recognizes two types of ash:

Class F - ash derived from anthracite and bituminous coals possessing pozzolanic properties, and

Class C - ash derived from lignite and sub-bituminous coals possessing pozzolanic properties as well as self-hardening properties.

The main difference between these two types of ashes is the calcium content. Class F ashes usually contain less than 5% CaO, while Class C ashes usually contain 15-30% CaO. In general, the crystalline minerals in low calcium fly ash are non-reactive, whereas many of the crystalline minerals in high calcium fly ash are reactive and capable of imparting cementitious characteristics to the fly ash. Since the non-crystalline phase or glass is the major component of fly ash (sometimes up to 90%), it appears that reasons for high reactivity of high calcium fly ashes also lie in the composition of the glassy material. The chemical composition of the glass in high calcium fly ash is different from that of the glass present in low calcium fly ash.

High calcium Class C fly ash usually contains very little (less than 1%) unburned carbon. In Class F fly ash about 2% to 10% unburned carbon is quite common. The carbon present in low calcium fly ash is capable of adsorbing a large amount of water and chemical admixtures from an aqueous solution. Use of such fly ash as a mineral admixture in concrete increases water requirements as well as the quantity of air entraining agent necessary to produce a frost resistant concrete. The surface characteristics of ashes also influence water demand and reactivity. Rough textured and porous glassy spheres, which are sometimes present in Class C fly ashes, possess larger surface area and are more reactive than smooth spheres (Mehta, 1983).

Alberta ashes are marginally sub-bituminous Class C ashes. They are slightly self-hardening in addition to being pozzolanic.

The relationships between pozzolanic activity and chemical and physical characteristics of some Canadian fly ashes are presented in detail by Joshi and Malhotra (1988).

3. HIGH FLY ASH CONCRETE

3.1 General

Since cement is the most cost and energy intensive component of concrete, replacement of cement with fly ash reduces the unit cost of concrete and also conserves energy. Introduction of fly ash in concrete also helps in reducing the fine aggregate requirement and thereby conserves rapidly diminishing sources of quality aggregate.

By incorporating more fly ash in concrete to replace cement, ash utilization can be improved significantly. However, such concrete mixes should have favourable strength, durability, and workability characteristics for effective practical applications. Therefore, clear understanding of the physical, chemical and mechanical properties of high fly ash concrete mixes is of great importance. This chapter reviews the properties of fresh and hardened concrete mixes containing high amounts of fly ash. Particular attention is given to mixes having high compressive strength.

3.2 High Strength Concretes

High strength concretes can be classified broadly into three groups:

(i) concretes with strength ranging from 35 to 70 MPa, used over the past ten years in a number of construction applications,

(ii) concretes with strength ranging from 70 to 100 MPa, and

(iii) concretes with compressive strength of more than 100 MPa.

Most of the high strength concretes used in building applications have nominal strength of about 62 MPa.

3.3 Use of Fly Ash in Concrete

One of the most common uses of fly ash is in cement concrete. Fly ash can be introduced into concrete in one of the following two ways:

(i) a blended cement containing fly ash may be used in place of portland cement, or
(ii) fly ash may be introduced as an additional component at the concrete mixing plant.

The first method is simpler and provides more uniform control.

Fly ash concretes can be divided into two types, depending on the percentage of fly ash used to replace portland cement. They are concretes containing less than 40% of the cementitious material as fly ash and ones containing more than 40% of the cementitious material as fly ash. The latter are generally termed high fly ash concretes.

3.4 Effect of Fly Ash Addition on the Properties of Fresh Concrete

3.4.1 General

The inclusion of fly ash affects all aspects of concrete properties. Fly ash can act in part as a fine aggregate and in part as a cementitious component. Rheological properties of the fresh concrete, and the strength, finish, porosity, and durability of the hardened material are all altered by the addition of fly ash.

In the freshly mixed state, fly ash acts as a fine aggregate and to some degree reduces the water cement ratio for the same workability. As soon as water and cement are mixed, reactions commence that ultimately produce the binder in the consolidated concrete mass. New particles are formed and original particles are dissolved or coated with cementitious products. The forces of dispersion, flocculation, and gravity compete to determine the spatial distribution of the materials in the changing mass. Heat is released due to hydration of cement and the temperature rises. In all of these events fly ash plays some role. Low calcium fly ash will act largely as a fine aggregate of spherical form initially but with time will react to form pozzolanic compounds. High calcium fly ash, on the other hand, may participate in the early cementing reactions, in addition to being part of the particulate suspension (Berry and Malhotra, 1987).

3.4.2 Effect of Fly Ash on the Setting Time of Fresh Concrete

Lane and Best (1982) noted that the influence of fly ash present in concrete on its setting time is less than the influence due to cement fineness, the water content of the paste and the ambient temperature. In general, low calcium fly ashes show a degree of retarding on cement setting (Dodson, 1981 and Berry and Malhotra, 1987). This type of behavior is evident in Table 3.1 corresponding to concretes containing various Canadian fly ashes.

Rodway and Fedirko (1985) and Ramakrishnan et al. (1981) reported an increase in setting time due to introduction of high calcium fly ash in concrete. The setting time determination tests conducted by Rodway and Fedirko resulted in an initial setting time of 7.5 hours at ambient temperature for the control concrete mix with no fly ash but containing a normal amount of superplasticizer and a water reducing agent (Table 3.2). However, as is evident from data in Table 3.2, highly superplasticized fly ash concrete mixes yielded increasingly lengthy initial setting times between 22 hours to 42.5 hours with increasing fly ash content (from 56% to 76% of the total cementitious content). The mix proportions of the concrete used in the above tests are also listed in the same Table.

Superplasticizing agents (high range water reducers) are used in concrete to reduce the quantity of water in the mix, while maintaining the same slump and amount of cementitious material, thus achieving very low water to cementitious material ratios (Table 3.2).

Table 3.1 Mix proportions and properties of concretes incorporating some Canadian fly ashes*.

Mix no.	Cement (kg/m^3)	Fly Ash (kg/m^3)	Fine Agg. (kg/m^3)	Coarse Agg. (kg/m^3)	AEA (ml/m^3)	W/(C+F)	Slump (mm)	Air (%)	Unit wt. (kg/m^3)	Bleeding (%)	Setting time (h:min)	
											Initial	Final
Control	295	0	782	1082	170	0.50	70	6.4	2320	2.9	4:10	6:00
F1	236	59	780	1077	320	0.50	100	6.2	2300	3.1	4:50	8:00
F2	237	59	782	1080	200	0.50	105	6.2	2310	4.6	7:15	10:15
F3	238	59	786	1088	200	0.50	100	6.2	2310	5.1	5:20	8:10
F4	237	59	792	1094	160	0.50	110	6.3	2320	4.3	6:20	8:25
F5	238	59	782	1080	690	0.50	65	6.4	2310	2.7	5:15	8:55
F6	238	59	784	1082	660	0.50	75	6.5	2300	2.6	4:30	6:50
F7	239	59	780	1077	370	0.50	100	6.1	2300	2.9	4:15	6:20
F8	236	59	775	1069	230	0.50	115	6.2	2300	5.6	5:10	7:30
F9	236	59	775	1070	240	0.50	100	6.4	2280	4.4	5:25	9:00
F10	237	59	781	1079	290	0.50	130	6.5	2290	2.5	4:45	7:00
F11	237	59	782	1080	150	0.50	140	6.6	2290	0.6	4:00	6:05

* From Berry and Malhotra, 1987

Table 3.2
Mix porportions, Properties of Fresh Concrete and
Summary of Compressive Strength of Western Canadian Fly Ash Concrete
(From Rodway and Fedirko, 1985)

Mix No.	1	2	3	4
W/C+F	0.41	0.28	0.28	0.28
F/C+F	0	0.56	0.68	0.76
Batch Quantities kg/m^3				
Cement (ASTM Type 1)	275	145	110	82
Fly Ash (ASTM Class C)	0	185	235	258
Sand	845	800	800	775
Gravel	1100	1100	1100	1100
Water	112	93	97	95
Air Entraining Agent ml/m^3	470	250	375	250
Water Reducer ml/m^3	1290	690	517	402
Superplasticizer ml/m^3	5.2	8.0	9.0	9.0
PROPERTIES OF FRESH CONCRETE				
Temp. °C	14	14.5	14	14
Slump mm	140	125	150	150
% Air Content	5.0	5.8	5.6	6.0
Density kg/m^3 *	2362	2374	2339	2317
Initial Setting Time (h:min)	7:32	22:09	30:45	42:44
COMPRESSIVE STRENGTH (MPa)				
152 x 305 mm Test Cylinders+				
1 day	9.8	--	--	--
3 days	25.4	18.5	8.4	2.4
7 days	31.6	28.9	17.6	7.7
28 days	36.7	50.6	39.8	22.7
56 days	40.5	59.3	49.2	28.4
91 days	42.1	65.8	56.3	31.3
102 x 203 mm Drilled Cores				
7 days	27.2	24.8	15.3	8.5
28 days	34.0	36.1	27.3	19.4
56 days	33.3	39.0	34.5	23.6
91 days	37.4	43.7	39.2	26.6

* At the time of demolding

+ Each value is average of two cylinders

3.4.3 Effect of Fly Ash on Workability of Fresh Concrete

Utilization of a bituminous fly ash in concrete generally reduces the amount of water required for a given degree of workability from that required for an equivalent paste without fly ash (Berry and Malhotra, 1987).

From the experimental studies conducted by Joshi et al. (1987) it is seen that workability of concrete, containing a water reducer and an air-entraining agent, increased when three sub-bituminous fly ashes from Alberta (Forestburg, Sundance, Wabamum) were used to replace 50% of the cement (see Table 3.3). The workability of the fresh concrete was assessed by the slump and Vebe consistometer test (ACI Standard 211.3-75).

Generally a better workability is indicated when the slump is higher (in excess of 60 mm) or when VEBE time is lower. As seen from Table 3.3, the fly ash concrete mixes even without air-entraining agents showed higher workability than the control mix without fly ash. However, concrete mixes without any water reducing agent and air-entraining agent did not achieve good workability. Increase in workability due to addition of Alberta fly ash to the concrete is not very apparent under these circumstances.

Haque et al. (1988) observed that the increase in workability due to the addition of sub-bituminous fly ash from Alberta replacing up to 50% of cement in concrete is most pronounced in concrete mixes with low and high strength.

The major factor influencing the effect of ash on the workability of concrete is the proportion of particles coarser than 45 μm in the fly ash (Owens, 1979). It is reported that substitution of 50% by mass of the cement with fine particulate in fly ash can reduce the water demand by about 25%. Similar substitution using fly ash containing 50% by mass of particles greater than 45 μm has no effect on water demand. The small size and spherical shape of fly ash particles have been credited with causing the reduction in the amount of water required for a given degree of workability from that required for an equivalent paste without fly ash.

Table 3.3 Properties of Fresh Concrete Mixes (From Joshi et al., 1987)

Mix	Ash Type	Slump (mm)	VEBE (s)	Density (kg/m^3)	Air (%)	Air-Entraining Agent (ml/kg cem. + ash)
No chemical Admixtures						
1A	Control	5	6.9	2422	2.8	
2A	Forestburg	20	5.4	2370	2.2	
3A	Sundance	10	5.8	2387	1.8	
4A	Wabamun	0	6.3	2387	1.7	
5A	Boundary Dam	20	5.4	2401	1.7	
6A	Laramie	20	5.5	2402	2.1	
7A	Lakeview	0	5.5	2387	2.2	
8A	Nanticoke	0	5.6	2394	2.7	
9A	Lingan	25	4.8	2401	2.0	
10A	Limestone	5	6.6	2401	1.8	
11A	Silica	0	10.6	2415	2.1	
Water-reducer with no air-entraining agent						
1B	Control	25	4.6	2415	1.8	
2B	Forestburg	120	2.2	2387	1.9	
3B	Sundance	170	1.4	2429	0.6	
4B	Wabamun	65	1.8	2401	1.7	
5B	Boundary Dam	125	1.2	2429	1.3	
6B	Laramie	110	1.9	2387	2.2	
7B	Lakeview	0	4.6	2430	2.5	
8B	Nanticoke	20	4.6	2401	2.5	
9B	Limestone	35	3.4	2394	2.5	
10B	Silica	30	3.1	2430	1.4	
Air-entraining agent with no water reducer						
1C	Control	20	6.7	2274	7.1	0.7
2C	Forestburg	25	4.0	2288	6.0	1.3
3C	Sundance	50	2.0	2267	6.6	2.2
4C	Wabamun	30	2.1	2281	6.0	1.6
5C	Boundary Dam	80	1.3	2274	6.2	3.8
6C	Laramie	50	2.8	2295	7.0	1.0
7C	Lakeview	0	4.7	2302	6.4	8.0
8C	Nanticoke	15	3.7	2323	6.0	5.4
9C	Lingan	60	1.3	2295	6.6	0.9
10C	Limestone	30	2.3	2288	6.5	1.8
11C	Silica	18	5.6	2260	6.5	2.1
Both water reducer and air-entraining agent						
1D	Control	60	5.2	2316	6.0	0.7
2D	Forestburg	110	1.6	2196	7.4	1.0
3D	Sundance	120	1.6	2316	6.5	1.4
4D	Wabamun	120	0.9	2260	6.1	1.2
5D	Boundary Dam	150	0.8	2302	6.2	2.2
6D	Laramie	165	1.5	2401	7.2	1.0
7D	Lakeview	5	4.3	2302	6.0	5.2
8D	Nanticoke	20	3.2	2302	6.0	2.0
9D	Lingan	175	0.4	2288	6.1	1.3
10D	Limestone	55	1.9	2290	5.8	1.5
11D	Silica	40	2.0	2302	6.6	1.7

* 50% replacement of cement by mineral admixture in all mixes except Nos. 1A - D.

1A-D - control mix with no fly ash
2-9 - type of fly ashes used
For all the mixes:
Water cement ratio = 0.47
Water reducer used = 7.11 ml/kg of cementitious material.

3.4.4 Effect of Fly Ash on Temperature Rise of Fresh Concrete

Hydration of portland cement is accompanied by generation of heat that results in a temperature increase in concrete. Partial replacement of cement by fly ash results in a reduction in temperature rise in fresh concrete (Rodway et al., 1985, Silvasundaram et al., 1987, and Langley et al., 1989). Rodway et al. (1985) used high amounts (up to 76% of total cementitious material) of Western Canada sub-bituminous fly ash, while Silvasundaram et al. (1987) and Langley et al. (1989) employed high volumes of Class F fly ash concrete in their studies.

Low calcium fly ashes generally tend to reduce the rate of temperature rise more than high calcium fly ashes (Berry and Malhotra, 1987). Reduction in the temperature rise in fresh concrete due to addition of fly ash is of particular importance in mass concrete where cooling following a large temperature rise can lead to cracking.

3.4.5 Effect of Fly Ash on Air-Entrainment in Fresh Concrete

Air-entraining agents (AEA) are added to the concrete during mixing, to obtain the desired number of correctly spaced air voids that are necessary for frost resistance in hardened concrete. Use of fly ash is known to increase the quantity of air-entraining agent required to produce a given level of air-entrainment, around 6%, in fresh concrete (see Table 3.3).

Experimental studies conducted by Gebler and Klieger (1983) suggested that concretes containing Class C fly ash generally require less air-entraining admixture than those concretes with Class F fly ash. Haque et al. (1988) observed that for a replacement level of 50% cement by either of two sub-bituminous fly ashes from Alberta, the average demand of air-entrainment agent was more than double that of the plain concrete. Therefore, Alberta fly ashes seem to behave in a different way than the Class C fly ashes studied by Gebler and Klieger (1983).

3.5 Effect of Fly Ash on the Structural Properties of Hardened Concrete

3.5.1 General

Presence of fly ash affects the properties of hardened concrete, such as strength development, elasticity, creep, shrinkage and thermal expansion. The type and the amount of fly ash utilized to replace cement greatly influences the mechanical properties of hardened concrete.

3.5.2 Effect of Fly Ash on Strength Development

3.5.2.1 Factors Influencing Strength Development Fly Ash Concrete

The degree and the manner in which fly ash affects workability is a major factor in its influence on strength development. Mix proportions can be selected for any desired rate of strength development. The rate of strength development in fly ash concrete is also influenced by the properties of fly ash, such as chemical composition, particle size, reactivity, temperature and other curing conditions (Berry and Malhotra, 1987).

3.5.2.2 Effect of Fly Ash Type and Proportion on Concrete Strength

Class C fly ashes generally affect the rate of strength development in concrete only marginally. Class F fly ashes, especially those produced in older power plants and having a large proportion of coarser particles, reduce the rate of strength development.

The type of fly ash can significantly affect the results when used in large volumes in concrete. Relatively more data is available on strength characteristics of concrete containing Class F fly ashes. Results of research by Swamy and Mahmud (1986) show that concrete containing 50% low calcium bituminous fly ash replacement and a superplasticizing agent, is capable of developing 60 MPa compressive strength at 28 days, and a fairly high strength at 3 days of the order of 20-30 MPa. Such concretes should be able to meet all the strength requirements of most reinforced and prestressed concrete in structural applications.

Compressive strength data of sub-bituminous fly ash (Forestburg, Sundance and Wabamum ash) concrete mixes made by replacing 50% cement are shown in Figures 3.1a and 3.1d (Joshi et al., 1987). Although in these figures strength data of concrete with a number of mineral admixtures are shown, in the following discussion the concrete mixes containing fly ashes from Alberta are mainly considered. The figures illustrate the strength of concretes at various ages and also the influence of addition of chemical admixtures (air-entraining agent and water reducing agent) on the concrete strength. The properties of fresh concrete and the proportions of chemical and mineral admixtures used in the various mixes are given in Table 3.3.

Figure 3.1a shows the strength of the concrete mixes without the addition of chemical admixtures. Introduction of the fly ashes into the concrete reduces the 7 day strength. However, at 56 days the loss in strength due to the addition of fly ash is recovered.

Figures 3.1b indicates that when water reducer is added to the concrete the strength is increased in the case of Forestburg fly ash concrete, while for concretes with Sundance and Wabamum ashes the strength is reduced.

The effect of air-entrainment in concrete on its strength is shown in Figure 3.1c. The data in the figure indicates that the early (7 day) and long term (56 day) strength of the concretes with and without the mineral admixture decreased due to the addition of air-entraining admixture in all cases except Forestburg fly ash concrete mix. In Forestburg concrete the long term strength did not alter due to the addition of an air-entraining agent.

The combined effect of air-entraining and water reducing admixtures on the strength of concrete mixes are shown in Figure 3.1d. The data in the figure indicates that, in general, strengths of concrete mixes containing both chemical admixtures were higher than the corresponding strengths of concretes with only air-entraining agent (C mixes, Figure 3.1c); but, lower than the corresponding strengths of concretes with only water reducer (B mixes, Figure 3.1b). Addition of chemical admixtures reduced the 56 day strength of all concrete mixes by about 5% to 30% when compared to concretes with no chemical additives.

Rodway et al. (1985) observed that 28 day strength of concrete mixes, where Western Canada fly ash (ASTM Class C) comprised of 56% and 68% of the total cementitious material, exceeded the standard 28 day cylinder strength of the non-fly ash control mix (Table 3.2). A greater compressive strength advantage was observed at later ages for the two fly ash mixes. However, a mix containing 76% fly ash did not perform as well as the non-fly ash control mix even at later ages (91 days). The strength results of this mix at earlier ages, up to 28 days, were considered too low for practical use in structural concrete.

Haque et al. (1988) reported that high quality sub-bituminous fly ashes from Alberta can be used, under proper curing conditions, to prepare concrete at 35% to 50% replacement of cement by weight, which attain 80% to 100% of the strength of an equivalent plain concrete after being cured for 90 days.

For concrete mixes with 40% to 75% sub-bituminous fly ash (ASTM Class C) replacing cement, an increase in flexural strength between 28 and 91 days of the order of 30% was observed by Haque et al. (1984). This increase in flexural strength was slightly less than the increase in compressive strength noticed for the same concrete mixes during the same period of time.

The results from flexural strength and splitting tensile tests on concrete with Eastern Canada fly ash (Class F), indicated a trend for these strength properties to be slightly lower than those of the control mixes without fly ash (Table 3.4).

Fig 3.1 Summary of Compressive Strength Results of Various Fly Ash Concrete Mixes (Joshi *et al.*, 1987)

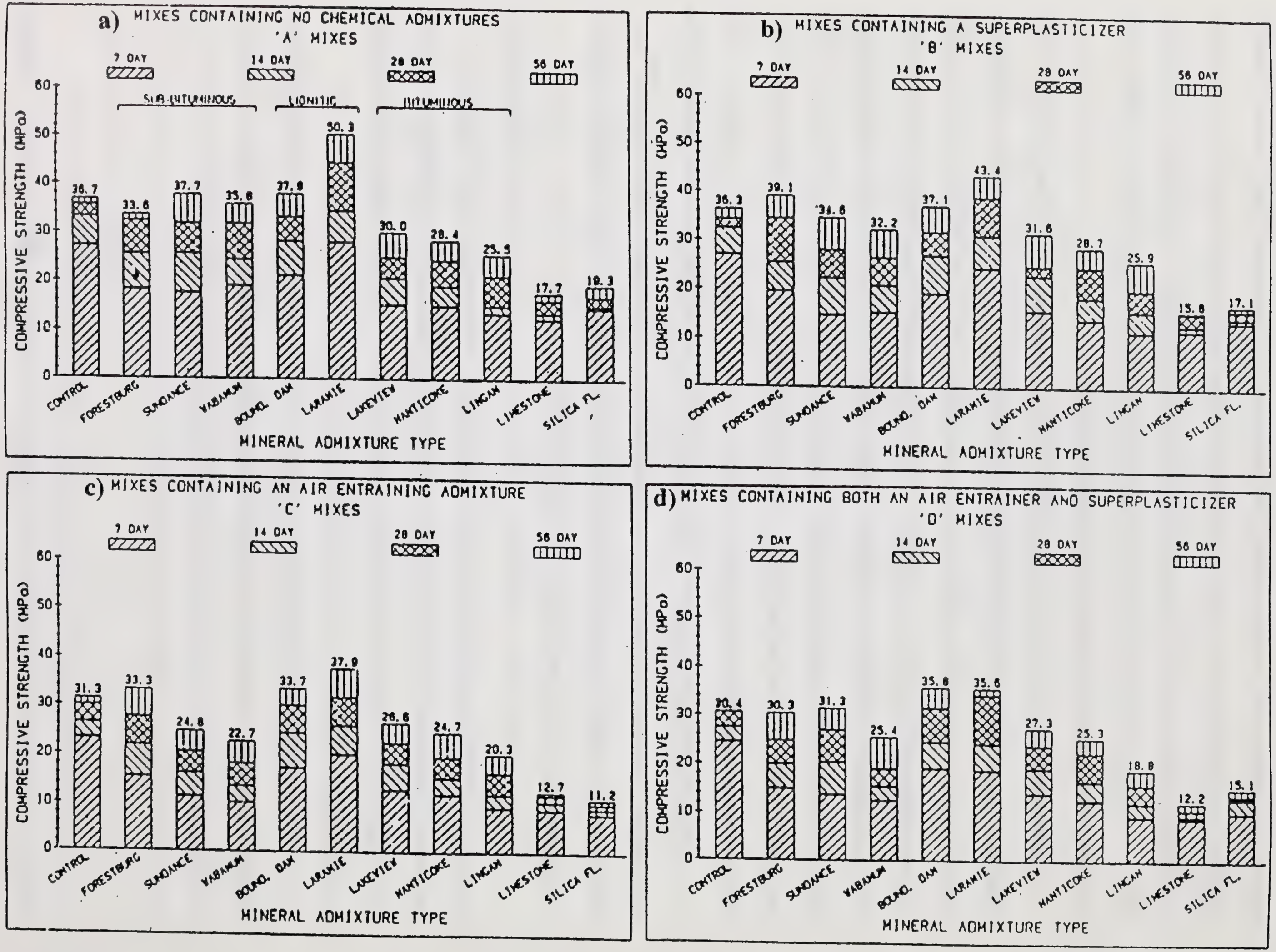

Table 3.4 Mechanical Properties of Hardened Concrete (From Langley, 1988)

Cement Type	Mix No.	W/C+F	Flexural Strength, MPa				Splitting Tensile (MPa)		Modulus of Elasticity, GPa	
			14 d	28 d	91 d	365 d	28 d	365 d	28 d	365 d
I	0	0.20	--	--	--	--	--	--	--	--
	1	0.28	7.6	--	9.6	--	--	--	36.1	--
	$1C^+$	0.39	8.0	--	--	--	--	--	31.5	--
	2	0.30	--	6.9	--	9.0	4.2	9.0	35.1	46.6
	$2C^+$	0.39	--	7.8	--	8.3	4.1	4.0	36.8	38.2
	3	0.33	6.5	--	8.9	--	--	--	33.8	--
	$3C^+$	0.45	7.0	--	7.4	--	--	--	28.9	--
	4	0.35	--	6.0	--	7.5	3.8	4.8	31.6	34.5
	$4C^+$	0.46	--	7.4	--	7.0	4.1	3.2	34.9	34.4
	5	0.49	--	--	*	*	2.9	*	27.9	*
III	6	0.30	--	7.3	--	9.2	4.1	5.5	32.7	46.1
	$6C^+$	0.39	--	8.6	--	7.0	4.7	4.2	32.2	36.3
	7	0.35	--	6.4	--	8.0	3.3	4.5	32.1	43.1
	$7C^+$	0.46	--	7.0	--	6.4	3.8	3.5	32.6	34.8

Note:
-- Indicates Test Was Not Performed
* Indicates Results Not Yet Available
+ Control Concrete Mix with no Fly Ash
All other mixes contained 50% fly ash with respect to total cementitious material.

3.5.2.3 Effect of Temperature on Strength Development in Fly Ash Concretes

When concrete made with portland cement is cured at temperatures in excess of 30°C, an increase in strength is observed at early ages, but a marked decrease in strength is noted in the mature concrete. However, the behavior of fly ash concrete is significantly different. Figure 3.2 shows the general trend in which the temperature rise during early ages of curing influences the 28 day strength. Fly ash concretes show strength gains as a consequence of heating in contrast to the loss of strength with portland cement concrete.

The sensitivity of fly ash to elevated temperature implies that it may also be sensitive to reduced temperature. Hence, more attention is required to curing fly ash concretes in cold weather. In general, concretes with or without fly ash, when cured at lower temperatures, develop high ultimate strength. Nonetheless, the rate of strength development is severely affected in concretes at early stages of curing at lower temperatures. This is of significance in Alberta.

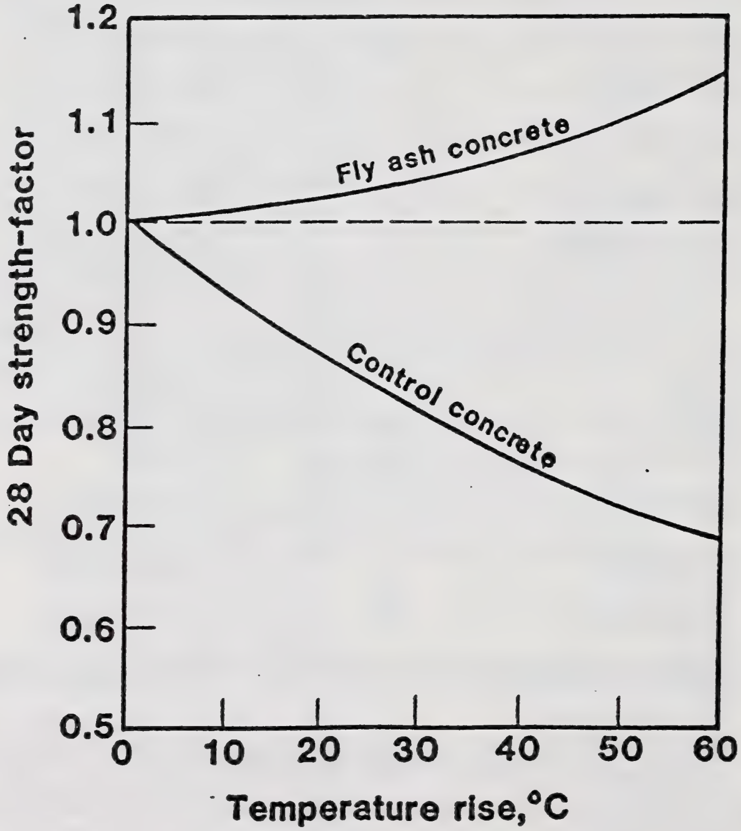

Fig 3.2 Effect of Temperature Rise During Curing on the Compressive Strength Development of Concrete (Berry and Malhotra, 1987).

3.5.2.4 Effect of Curing on Strength Development in Fly Ash Concrete

Poor curing conditions affect the strength of all fly ash concretes, in particular those with a high proportion of ash, much more than the strength of plain concrete. Test results of mixes with sub-bituminous fly ashes from Alberta replacing up to 50% cement, showed that the lower the ash content in the mix the smaller the reduction in strength due to poor curing (Haque et al., 1988). In these tests curing was done at 50% relative humidity at room temperature. From the test data the effect of poor curing on strength was not apparent before 8 days because the test cylinder contained sufficient residual water for hydration to continue.

Gifford et al. (1987) studied the drying of concrete specimens at 5°C and 0°C made with 40% cement replaced by a sub-bituminous fly ash from Alberta. The test results showed that within 50 hours after casting, normally 30% and 60% of the mixing water was lost through evaporation from unprotected surfaces while exposed to 50% and 10% relative humidity respectively. In addition to the strength loss due to evaporation of water, Gifford et al. hypothesized that the combination of low curing temperature and the cooling effect of evaporation of water at low relative humidity retards the rate of hydration and, therefore, strength development. The importance of curing concrete in an enclosed environment, particularly at low temperatures, was stressed in order to reduce the effect of evaporation during the initial hours of pouring concrete.

Considering the satisfactory level of strength development at 28 days for a high fly ash concrete (with Class F fly ash) that had been moist cured for 3 days, Langley et al. (1989) concluded that curing periods beyond those that are normal in construction practice are not necessary. They pointed out that in relatively large structural elements, the long term strength development of such fly ash concrete in the interior mass is likely to be less influenced by drying than the test cylinders used in the laboratory.

Development of strength with age under different curing regimes for three high fly ash concrete mixes was studied by Swamy and Mahmud (1986) and the results are shown in Table 3.5. Increase in strength of 50% to 100% over the 28 day strength was attained after one year due to continuous moist curing. For two other curing regimes (one with 7 day moist curing followed by air drying and the other with continuous air drying), strength increases at one year of 6% to 22% over the 28 day strength were recorded. Continuous moist curing of normal concrete, on the other hand, resulted in only 18% to 25% increases in strength after one year.

Table 3.5 Rate of Strength Development as percentage of 28 day strength*.

Age (days)	Strength, (MPa)								
	20			40			60		
	FOG	DRY	7F+D	FOG	DRY	7F+D	FOG	DRY	7F+D
1	19	--	--	25	--	--	34	--	--
7	55	71	--	67	80	--	68	79	--
28	100	100	100	100	100	100	100	100	100
150	176	125	104	140	119	105	135	123	117
270	197	114	110	150	125	116	140	113	121
365	209	118	106	162	122	107	146	116	118

* From Swamy and Mahmud (1986)

3.5.3 Effect of Fly Ash on Elastic Properties of Concrete

Fly ash properties which control compressive strength also influence the modulus of elasticity. The modulus of elasticity of fly ash concrete is generally lower at an early strength (Langley, 1988) and higher at an ultimate strength compared to concrete without fly ash (Rodway et al., 1985).

3.5.4 Effect of Fly Ash on Load Independent Volume Change

Munday et al. (1982) reported that incorporation of fly ash does not significantly affect the drying shrinkage, wetting/drying expansion or thermal expansion of concrete.

Yuan and Cook (1983), from their studies of concrete using high calcium fly ash, concluded that the replacement of cement between 20% to 50% by fly ash has little influence on drying shrinkage. However, tests conducted by Haque et al. (1984) on concrete with 40% to 75% cement replaced by a sub-bituminous fly ash (ASTM Class C) indicated that drying shrinkage of concrete decreased with increase in fly ash content. From the literature, it is evident that introducing fly ash in concrete mixes, in general, has little influence on the load independent volume change (shrinkage or expansion) of the concrete.

3.5.5 Effect of Fly Ash on the Durability of Concrete

3.5.5.1 General

Internal and external causes lead to failure of concrete after several years and reduce the life span for which it was designed. External causes may be physical or chemical in nature; eg. weathering, extremes of temperature, abrasion or chemical action on the cement hydrates, aggregate or reinforcement components. Internal causes may lie in the choice of materials or inappropriate combinations of materials.

Of all the causes of lack of durability in concrete, the main one is excessive permeability. Concrete must be relatively impervious to allow it to withstand freeze thaw cycles in cold regions.

3.5.5.2 Effect of Fly Ash on Permeability of Concrete

At early ages, fly ash concretes containing high calcium or low calcium fly ashes, at up to 50% of cementitious materials, are more permeable than concretes without them. But, after six months this trend reverses. Considerable imperviousness develops in a matter of six months in concrete containing fly ash, most likely because of pozzolanic influence of fly ash (Davis, 1954).

3.5.5.3 Effect of Fly Ash on Freeze-Thaw Durability

It is well known that air content has the greatest influence on freeze-thaw resistance of concrete. Virtanen (1983) observed that addition of fly ash has no major effect on the freeze-thaw resistance of concrete if the strength and air content are maintained constant.

Freezing and thawing durability of fly ash concretes containing low or high calcium fly ashes up to 20% of replacement of cement, is superior to those containing no fly ash. But, on increasing fly ash content to 50%, scaling damage seems to increase (Yuan and Cook, 1983).

Freeze-thaw tests conducted by Joshi et al. (1987) on concrete with 50% of the cement replaced by Sundance and Wabamum fly ashes yielded relative dynamic modulus values in excess of 60% after 300 cycles. This indicates that the particular high fly ash concrete mixes were reasonably durable. It was also observed that there were no significant differences in relative dynamic modulus values between air-entrained high fly ash concrete mixes and those mixes containing both air-entraining and water reducing agents. However, test specimens without air-entrainment failed at less than 50 freeze thaw cycles indicating a low level of durability. All the concrete mixes made with the two Alberta fly ashes showed some scaling after 150 to 200 freeze thaw cycles and exhibited about 2% weight loss at the end of the test.

3.5.5.4 Effect of Fly Ash on Concrete Exposed to Salts

From the experimental studies conducted by Joshi et al. (1987) it can be seen that replacement of 50% cement by Sundance and Forestburg fly ashes enhances the sulphate resistance of sand-cement mortar. Work of Kalousek et al. (1972) leads to the conclusion that fly ashes are prominent among the group of pozzolans that significantly increase the life expectancy of concrete exposed to 2.1% sodium sulphate solution.

Scaling resistance tests using calcium chloride salt solution on a concrete mix with 40% of cement replaced by a sub-bituminous fly ash from Alberta showed very slight to slight scaling (Gifford et al., 1987).

At present, there is a lack of direct information with regard to the effect of fly ash on concrete exposed to sea water (Berry and Malhotra, 1987). Permeability is considered as the major factor affecting durability of concrete in sea water. From the general properties of high fly ash concrete it is evident that fly ash has the potential to contribute to a number of aspects of concrete durability in a marine environment.

3.6 Applications of High Fly Ash Concrete

Tarun et al. (1989) presented two case histories involving applications of very high fly ash content concrete in the field. In one case, a concrete mix with 70% of cement replaced by Class C fly ash was used to pave a 254 mm thick roadway. In order to obtain high durability and workability an air-entraining agent and a water reducer were added to the concrete mix. The air content of the concrete was kept between 5% to 6% using the air-entraining agent. The use of water reducing improved the workability of the concrete. The main problem encountered with the completed roadway was that the rate of gain in compressive strength was slower than anticipated. The condition of the roadway surface was excellent with no defects observed.

The other case reported by Tarun et al. (1989) involved placing of the same high fly ash concrete mix mentioned above for a number of 138,000 volt transformer foundations measuring 4.9 x 5.5 x 1.5 m. No problems were reported during or following the construction.

In both these projects using high percentages of fly ash to replace cement in the concrete a considerable economic gain was achieved.

Haque et al. (1984) from tests conducted on sub-bituminous high fly ash concrete mixes, concluded that concretes with fly ash to cementitious ratios up to 75% (with total cementitious fractions between 325 to 400 kg/m^3) may give adequate strength, durability and volume stability for surface applications in pavement structures. It was also indicated that low workability high fly ash concretes with high range water reducers can be very attractive for base course applications in pavements due to the considerable ease in compaction of such materials.

Gifford et al. (1987) showed that concrete with high quality Alberta fly ash replacing cement by 40% can be used in curb and gutter construction. Results from their field and laboratory tests suggested that with adequate field curing the strength of fly ash concrete curb and gutter can be equal to or better than plain concrete and that the strength satisfied the minimum 28 day strength requirements. Air content of around 6.5% in the high fly ash concrete mixes provided a freeze-thaw durability that is similar to the control concrete mix with no fly ash.

Langley et al. (1989) reported two case histories where high fly ash concrete was used with 55% cement (ASTM Type 1) replaced by a fly ash (ASTM Class F) along with an air-entraining agent and a superplasticizer. In one case, where columns, beams and floor slabs in a building complex required 50 MPa concrete at 120 days, the high fly ash concrete used provided a 74 MPa compressive strength at 120 days, exceeding the strength requirement. No unexpected problems were reported and the high fly ash concrete proved to be an economical solution for the particular project.

In the second case, a similar high fly ash concrete was used in large diameter piles (greater than 1 m) with average length of about 21 m embedded 1.8 m deep into bed rock supporting a 22 storey office tower. Since the piles were heavily reinforced a superplasticizer was used to increase the workability. The 28 day design strength requirement of 45 MPa for the concrete used in piles was exceeded by the high fly ash concrete, with a strength of the order of 51 MPa after 28 days. In situ load tests revealed that bond strength developed between concrete and rock was quite adequate, with values exceeding 3 MPa, greater than the design requirement of 1.2 MPa.

Concretes containing high volumes of fly ash and very low water content have been used for dams, and base courses for highways, parking lots, and log storage areas in the pulp and paper industry (Joshi and Natt, 1983). This is referred to as roller compacted concrete or geocrete. The extremely low workability of such concretes precludes their use for normal applications for structural work.

The roller compacted concrete incorporating fly ash generally contains 60% to 80% of fly ash. The main function of fly ash in roller compacted concrete is to occupy space between larger particles by providing a large volume of fine material that would otherwise require the use of additional cement. In addition, fly ash in mass concrete contributes to reduction in the heat evolution and, hence, the temperature rise. This would reduce the chances of shrinkage cracks due to subsequent cooling of the concrete. ACI Committee 207 (1980) indicated that presence of both air-entraining and water reducing agents in roller compacted concrete may effectively reduce the vibration time for full consolidation of the concrete.

3.7 Conclusions from Literature Review

From the literature survey conducted on high fly ash concretes the following general conclusions can be made which are applicable for Class C type sub-bituminous fly ashes produced in Alberta for up to 60% replacement of the cement in concrete.

1. Fly ashes exhibit pozzolanic activity and also possess some self hardening properties, thereby participating in the hydration reactions in the concrete.
2. In the freshly mixed state fly ash acts as a fine aggregate.
3. Addition of fly ash into concrete reduces water demand without loss of workability, particularly when there is a considerable amount of particles finer than 45 μm in the fly ash.
4. Use of fly ash increases the quantity of air-entraining agents required to produce a given level of air-entrainment.
5. Addition of water reducer into high fly ash concretes has varying effects on strength for different types of Alberta fly ashes. In the case of Forestburg fly ash concrete, the strength increases, while for Sundance and Wabamum fly ash concretes, the strength reduces due to the inclusion of water reducer.
6. By using air-entraining agents, water reducing agents or superplasticizers in high fly ash concrete, along with proper curing conditions, mixes with high strength, durability and workability may be produced.

High fly ash concretes with Class C fly ashes, such as those produced in Alberta, are likely to have the following characteristics in comparison to concretes with no fly ash.

In the fresh state, high fly ash concretes have:

1. longer setting times,
2. lower strengths and lower modulus of elasticity,
3. reduced temperature rise due to hydration,
4. strength gains as a consequence of heating during early ages of curing in contrast to the loss of strength with portland cement,
5. lower tolerance to cold temperature and evaporation of water (drying) during curing, and
6. higher permeability than the concretes with no fly ash.

In the case of hardened concrete, high fly ash concretes have:

1. equal or higher strength,
2. higher modulus of elasticity,
3. lower drying shrinkage,
4. lower permeability,
5. higher resistance to sulphate attack, and
6. no significant difference on freeze-thaw durability over concretes with no fly ash.

The above properties of high fly ash concretes and observations made from particular applications of the mix in the field, may further lead to the following conclusions.

Advantages in using high fly ash (Class C) concretes are:

1. reduced construction costs,
2. greater tolerance to elevated temperatures during curing,

3. lower temperature rise during hydration making the mass concrete less susceptible to shrinkage cracks, and
4. provide mixes, particularly in the long term and under proper curing conditions, with superior strength, workability and durability properties.

The main disadvantages that are involved in using high fly ash (Class C) concrete are the longer setting time and lower rate of strength development. These factors require such concretes to be placed in formwork for a longer time than concrete with no fly ash and restrict early usage. Furthermore, under cold temperature conditions proper curing of high fly ash concretes is important, particularly during early ages, in order to minimize the lower rate of strength development.

From the results of the literature survey conducted in the present study, the following may be possible uses of high fly ash concretes.

High fly ash high strength concrete may be prepared with an air-entraining agent and a superplasticizer for structural elements such as floor slabs, beams and columns provided such a mix satisfied the initial strength requirements. High workability characteristics of high fly ash concrete mixes enhance its use in heavily reinforced structural elements.

High fly ash concrete mixes with proper chemical admixtures for providing adequate workability and durability could also be used in paving roadways and driveways of residential buildings. Low workability high fly ash concretes with high range water reducers can be very attractive for base course applications in pavements due to the considerable ease of compaction of such materials.

The literature search also suggests that research as described below needs to be conducted.

1. Adequate studies have not yet been conducted on use of sub-bituminous fly ash from Alberta replacing 50% or more cement in high strength concrete.

2. Methods of improving initial setting time and rate of initial strength development of high fly ash high strength concrete need greater attention.
3. Durability of high fly ash concrete mixes exposed to sea water environments have to be evaluated.

4. EXPERIMENTAL PROGRAM

4.1 General

This chapter outlines the experimental program that was undertaken in developing high strength concrete mixes, using high amounts of Alberta fly ash, with adequate durability and workability characteristics. The program also looked into the areas indicated in Section 3 that required investigation. A brief description of the materials used, the type of tests performed and testing procedures (including sample preparation technique) is outlined here.

4.2 Materials

This section describes the characteristics of various materials used in preparing fly ash concrete mixes. These materials include fly ash, cement, coarse and fine aggregate, superplasticizer, air entraining agent, and set accelerator.

4.2.1 Fly Ash

Three types of sub-bituminous (class C) fly ash, produced by coal burning plants in Alberta were used. These power plants are located in Sundance, Forestburg and Wabamun. Sundance and Wabamun fly ashes were supplied by Trans Alta Utilities, while Forestburg fly ash was supplied by Alberta Power plants. Both Sundance and Forestburg were classified fly ashes, whereas Wabamun was unclassified and was supplied in the form of raw ash. Fly Ashes are classified according to ASTM specification C-618 depending on gradation and chemical composition. The physical and chemical properties of the three types of fly ash are given in Table 4.1.

Table 4.1 Chemical and physical properties of fly ash.

Composition	Sundance	Wabamun	Forestburg
SiO_2	57.8	59.2	56.3
Al_2O_3	23.0	22.3	21.7
Fe_2O_3	3.5	3.9	4.9
CaO	10.6	9.9	9.0
MgO	1.5	2.1	1.2
K_2O	0.5	0.9	1.0
Na_2O	2.3	0.3	4.2
SO_3	0.3	0.2	0.4
LOI(%)	0.5	0.4	0.4
Specific gravity (g/cm^3)	2.04	2.17	2.01
Specific surface area (cm^2)	3140	3060	3690
Pozzolanic activity index	91.0	85.0	93.0

4.2.2 Cement

Normal portland cement, ASTM Type I, was used. High early strength cement, ASTM Type III, was also used in selected mixes for comparative purposes. The physical properties and chemical analyses of these cement types are given in Table 4.2.

Table 4.2 Chemical and physical properties of normal and high-early-strength concrete.

Composition	Cement Type I	Cement TypeIII
SiO_2	20.8	20.3
Al_2O_3	4.4	5.6
Fe_2O_3	2.6	2.0
CaO	62.7	62.2
MgO	4.4	1.4
K_2O	0.8	1.3
Na_2O	0.2	0.02
SO_3	2.5	5.4
LOI(%)	1.1	1.5
Specific gravity (g/cm^3)	3.14	3.12

4.2.3 Aggregate

4.2.3.1 Coarse Aggregate

The coarse aggregate that was used for the concrete was crushed semi-rounded limestone with maximum aggregate size of 14 mm. The specific gravity of the coarse aggregate was 2.65 and the dry-rodded unit weight 1700 kg/m^3. The aggregate was washed to remove all silty size particles, and was stored in a 100% humidity atmosphere, in a curing room, to achieve surface saturated dry (SSD) condition. Table 4.3 gives the grain size distribution of coarse aggregate. The coarse aggregate used in this testing program complied with ASTM C-33.

Table 4.3 Coarse Aggregates.

Sieve Size (mm)	Passing (%)
20	100
14	85.6
10	52.8
5	8.8
0.5	1.3
0.25	0.9

4.2.3.2 Fine Aggregate

The fine aggregate used in the concrete mixes was natural clean sand. The sand was in air dry condition. The fineness modulus of the sand is 2.83. The particle size distribution of the fine aggregate used in this study is shown in Table 4.4 and it is in accordance with ASTM C-33 specifications.

When determining the water cement ratio of the concrete mix, the amount of water used was adjusted for moisture of the coarse aggregate and for the absorptive capacity of the fine aggregates.

Table 4.4 Fine Aggregates.

Sieve Size	Passing (%)
5 mm	99.4
2.5	90.0
1.25	84.3
630 μm	60.3
315	21.4
160	5.0
Specific Gravity	2.64

4.2.4 Superplasticizers

High range water reducers, or superplasticizers, are highly effective dispersing agents. The dispersing effect, in a concrete mix, helps to separate cement particles that normally clump together and, therefore, allows more of the particles to react with the mix water. The efficient hydration of cement particles due to the presence of high range water reducers enables the mix to achieve low water cement ratios and, thereby, high strength.

Two types of superplasticizers were used in the study: WRDA-19 and Daracem-100. WRDA-19 is an aqueous solution of a modified naphthalene sulfonate containing no chloride. It is reported to have a marked capacity to disperse the cement agglomerates normally found in a cement-water suspension. WRDA-19 is formulated according to specification ASTM C494 for concrete as a Type A

Admixture. Daracem-100 is an aqueous solution of chemical dispersants combined with other chemicals which increase its beneficial effects on the quality and plasticity of a concrete mix. According to the producer, it is a highly versatile, dual-purpose admixture. By varying the dosage, it will meet the requirements of an ASTM C494 Type A Water Reducing Admixture, Type F Non-Retarding High-Range Water Reducer or as a Type G Retarding High-Range Water Reducer.

4.2.5 Air-Entraining Agents

Air-entraining admixtures are used to entrain air and thereby improve the durability of the concrete mix under freeze-thaw conditions. The type of air-entraining agent used was Daravair and it met the requirements of ASTM C260 for concrete. Daravair is an aqueous solution of completely neutralized Vinsol resin. It has the ability to facilitate entrapment of air during mixing of the concrete.

4.2.6 Set Accelerators

Set accelerating admixtures are normally used to reduce the setting time and to increase the early strength development of concrete. Darex set accelerator was used for a few selected trial mixes. It is a free flowing powder which does not contain calcium chloride and is designed to meet the requirements of ASTM C494 Type E. The effect of Darex on the setting time and development of early strength of the fly ash concrete was monitored.

4.3 TESTS

The types and methods of testing used in the present program are briefly outlined in this section.

4.3.1 Slump Test

The slump test was performed according to ASTM C143 on all concrete mixes to determine their workability. High workability, indicated by high slump, is needed for ready-mixed concrete to enable it to be easily handled with standard equipment. High workability concrete is also essential for casting of densely reinforced structural elements. A slump in excess of 100 mm is, usually, considered a high workability concrete for that application.

In the event the designer has not specified, a slump value of 50 to 100 mm is recommended by both Canadian (CAN3 - A23.1 - M77, CAN3 - A23.2 - M77) and American Standards (ACI 211.1-81) for concrete mixes used in the construction of reinforced structural elements. ACI publication SP-46 states that the optimum slump for pumping concrete should be generally in the range of 75 to 125 mm. Most of the literature dealing with high fly ash high strength concrete (Swamy and Mahmud, 1986; Langley et al., 1989; Rodway and Fedirko, 1985) indicated slump values ranging between 100 and 200 mm were used in their mixes. Langley et al. (1989) discussed two case histories (see section 3.6) where high fly ash high strength concrete mixes have been used. The slump values for these mixes were around 120 mm.

4.3.2 Air-Entrainment Test

The air content of the freshly mixed concrete was determined according to ASTM C-231 specifications by the "pressure method" using an air meter of Type B. The air content is directly read from the air meter which is calibrated based on the volume change of fresh concrete subjected to a confining pressure. All mixes with an air content of around 6% were considered adequate while mixes in excess of 8% or below 4% were discarded because of the adverse influence of air content on strength (when air content exceeds 8%) and frost resistance (when air content falls below 4%). The density of the fresh concrete was also determined during the air-entrainment test. This was done by recording the weight of concrete required to fill the mold used for air entrainment and the known volume of the mold.

4.3.3 Setting Time Test

The initial and final times of setting of the concrete mix were determined according to the standard specification ASTM C-403 by the penetration resistance method. The time of initial set is defined as the elapsed time after initial contact of cement and water, for the mortar to reach a penetration resistance of 3.5 MPa (500 psi). The time of final setting is defined as the time required to reach a penetration resistance of 27.6 MPa (4000 psi). The mortar was obtained by wet sieving freshly mixed concrete.The resistance of the mortar to penetration by standard needles was measured at regular time intervals after the initial contact occured between water and cementitious material. From the penetration resistance vs. time plot, the initial and final setting times were determined.

Bleeding of the concrete specimens was also monitored using the setting time test. Water was collected by a pipette before the penetration test was performed. The water collected in this manner provided an approximate value of the amount of bleeding.

4.3.4 Compressive Strength Test

The uniaxial compressive strength tests for the initial trial mixes were conducted at the ages of 7 and 28 days. For the final design mixes, the tests were conducted at the ages of 1, 3, 7, 28, 56, 120 days. Testing was performed at each age in accordance with the ASTM C-39 specification. At each age, three specimens from the same mix were used for compressive strength tests.

The fresh concrete was cast in cylindrical disposable molds, 7.62 mm (3 in.) in diameter and 15.24 mm (6 in.) in height, made of nonabsorbent material conforming to the requirements of specification ASTM C-470. The method of casting concrete is discussed in section 5. Before testing, the concrete cylinders were capped with high strength capping material utilizing high amounts of sulphur in order to ensure that no failure of the capping material would occur during loading.

The compressive strength tests were performed using an *Amsler* type uniaxial compressive strength testing machine, which has an ultimate capacity of 200 tonnes, at a constant loading rate of 1 kN/sec.

4.3.5 Freeze-Thaw Test

The freeze-thaw resistance of concrete specimens was determined according to the specifications of ASTM C-666 Procedure A. This test determines the durability of the concrete under cyclic freezing and thawing action. The specimens were cast in prism molds with dimensions of 7.6 x 7.6 x 35.6 mm (3 x 3 x 14 in.), in accordance with ASTM Method C-192 and specification C-490. After 14 days of curing, the specimens were transferred from the fog room to a tempering tank (temperature controlled between -1.1°C to 2.2°C) where they were conditioned for at least an hour and a half. The specimens were surface dried and their initial fundamental transverse frequencies were measured. The samples were then placed in freeze-thaw baths where they were completely surrounded by not less than 1 mm and no more than 3 mm of water at all times.

The specimens were subjected to rapid freezing and thawing in the baths and the number of freeze-thaw cycles were recorded automatically. Measurement of the fundamental transverse frequency was done every week, after every 30 to 40 freeze-thaw cycles, until the specimens had been subjected to 300 cycles or until their relative dynamic modulus of elasticity reached 60% of the initial modulus, whichever occurred first. Three concrete specimens of the same mix were tested for freeze-thaw durability.

4.4 MIX PROPORTIONING

In order to obtain an optimum mix design, a number of trial mixes were prepared with different cementitious material contents, fine to total aggregate ratios, water-cement ratios and with different amounts of air-entraining agent, superplasticizer, and set accelerator. Compressive strength tests at the age of 7 and 28 days were performed on the trial mixes to evaluate the optimum values of each of the above variables. According to the original proposal, the fly ash contents in the total cementitious material were to be 50% and 60%. However, in this test program an additional series of concrete mixes containing 40% fly ash replacement of cement was also prepared.

4.4.1 Cementitious Material Content

Different cementitious contents were used for the trial mixes. Fly ash and cement form the cementitious material of the concrete mix. The objective of this series of trial mixes was to achieve the required strength with minimum amounts of cement and fly ash, thus reducing the cost of concrete produced. To obtain an optimum cement content for high strength concrete mix design, ACI publication SP-46 recommends testing of trial mixes with cement contents varying between 380 kg/m^3 and 560 kg/m^3. In our test program, the cement contents (i.e. the total cementitious material content) used in the trial mixes were 380, 466, and 520 kg/m^3.

4.4.2 Aggregate Proportion

Different aggregate proportions were tried to achieve optimum values of strength, workability, and air content. The maximum size of the aggregates chosen was 14 mm. A volume of around 0.64 m^3 of dry-rodded coarse aggregate per one cubic meter of concrete is recommended by ACI SP-46 as an optimum amount corresponding to a maximum aggregate size of 14 mm. Based on the dry-rodded unit weight of 1700 kg/m^3, the weight of the coarse aggregate in a cubic meter of concrete was determined as 1088 kg. A value close to this amount was used for the concrete mixes. The optimum amounts of coarse aggregate recommended in ACI SP-46 for high strength concrete were the result of a modified version of Table 6 in ACI 613-64. The variation was necessary because of the extremely high percentages of cementitious material in the high strength concrete mixes. These mixes which were designed according to ACI 613-64 produced sticky mixes with a loss in workability. According to ACI SP-46, the modification of the coarse aggregates was more important as the maximum size of aggregate decreased.

It is mentioned in ACI SP-46 that the optimum sand content for a given size of coarse aggregate may not be critical over a broad range of values. Data presented in the above publication for high strength concrete mixes indicated an optimum strength corresponding to amounts of fine aggregate between 37% to 40% by weight of total aggregate. In this study, the amount of fine aggregate used in the mixes was varied between 36% to 42% of the total aggregate weight.

The air content depends, to some extent, on the amount of fines present in the aggregate. The ASTM C33 recommends a limit to the amount of fines in the aggregate for air-entrained concrete with an air content in excess of 3%. It recommends that no fines passing the 150 μm (No. 100) should be present in the coarse and fine aggregate. Thus, the coarse aggregates were washed to remove fines such as crusher dust and fines resulting from degradation and handling. The sand was sieved allowing for no fines passing the 150 μm sieve size.

4.4.3 Water Cement Ratio

The water cement ratio affects the strength, workability and air content of concrete mixes. As the water cement ratio is increased the concrete specimen exhibits lower density and higher void content with the resulting decrease in strength. The aim of this series of trial mixes was to achieve the minimum water cement ratio that would result in the highest values of strength without decreasing the air content below 5%. Recommendations from ACI SP-46 on maximum water cement ratio for high strength concrete were taken into account in deciding the amount of water to be added to the mixes. ACI SP-46 reports that the water cement ratio for mixes with strengths up to 63 MPa should not exceed 0.34. Very low water cement ratios, on the other hand, might have an adverse impact on the workability of the mix. Thus, to account for the slump loss, superplasticizers were used which resulted in fly ash mixes with water cement ratios as low as 0.28.

4.4.4 Air-Entraining Agent

The air-entraining agent, Daravair, was used in different proportions. These proportions ranged from 95 ml/100kg cementitious material up to as high as 450 ml/100kg cementitious material. The objective of this was, as stated before, to achieve an air content of around 6%.

4.4.5 Superplasticizer

Two types of high range water reducers or superplasticizers (Daracem-100 and WRDA-19) were used to achieve high workability in excess of 100 mm slump. The amounts of superplasticizer used ranged from 400 ml/100kg cementitious material to 2500 ml/100kg cementitious material.

4.4.6 Set Accelerator

Darex set accelerator was used for a few trial mixes to evaluate the effect on the setting time and the early strength development of the concrete specimens. Two amounts of Darex, 0.5kg/100kg cementitious material and 1.0kg/100kg cementitious material, were used.

4.5 MIXING AND SAMPLE CASTING PROCEDURE

4.5.1 Mixing

Mechanical mixing of the concrete was performed in a 0.081 m^3 (3 ft^3) capacity *Erich* type mixer. The mixer was dried and cleaned, to remove traces of water and other impurities that might exist from a previous mixing operation.

The coarse aggregate was added first with some of the mixing water prior to rotation of the mixer. The air entraining agent was mixed with water to achieve efficient mixing of the agent with the concrete. After it had been left running for a short time, the fine aggregates were introduced to the mixer . Then, the cementitious material consisting of cement and fly ash was added along with the remaining amount of water. Subsequently, the superplasticizer was slowly added to the mix while the mixer was still running to allow it to be uniformly mixed with the concrete.

Mixing was done for 3 minutes initially followed by 3 minutes rest and by 2 minutes of final mixing. In the final design mixes where relatively large quantities of superplasticizer were used, it was added in two stages. Initially, about 70% of the superplasticizer was added and mixing was performed according to the procedure outlined above. The remainder of the chemical admixture was then introduced to the concrete and the mixing was continued further for two minutes. As soon as the concrete mixing was over, a slump test was performed on a representative sample of the fresh concrete to determine the workability of the mix. Thereafter, an air entrainment test was conducted on the fresh concrete.

4.5.2 Casting

Once the slump and air entrainment tests were performed on the fresh concrete, a portion of the remaining mix was cast in two types of molds. One type, was the cylindrical shaped disposable molds, to be used for compressive strength testing; while the second type was prism shaped molds for freeze-thaw durability testing. The concrete was cast in the molds in two layers. Each layer was allowed to compact for approximately 1 minute or until the surface of the layer had become relatively smooth. Compaction of the concrete mix was achieved using a vibrating table. The surface of the first layer was roughened with a spatula to allow for proper cohesion or bonding with the second layer of concrete. The top surface of the concrete was levelled to achieve a horizontal, planar surface.

On completion of casting, the samples were covered with a thin polyethylene sheet to allow for proper hydration by minimizing any evaporation of water in the concrete. The samples were left, away from any source of vibration, for 24 hours. Then the samples were demolded and transfered to the fog room (maintained at a temperature of around 23°C and relative humidity of 100%) for curing and were kept until testing.

A setting time test was also performed for selected concrete mixes. For this test, a representative sample from the mix was wet sieved through a 4.75 mm (No.4) sieve to separate the coarser aggregate. The initial and final setting time tests were conducted on the resulting mortar in accordance with ASTM C-403.

5. TEST RESULTS AND DISCUSSIONS

5.1 Trial Mixes

The mix proportions, slump, air content and compressive strength at 7 and 28 days for the trial mixes are given in Appendix A. The proportions given are based on a yield of approximately one cubic meter of fresh concrete.

5.1.1 Effect of Cementitious Content

The optimum value of cementitious content per cubic meter of concrete was determined from a series of trial mixes. It was noted that the optimum cementitious content was the same for all fly ash mixes. As the cementitious content increased from 380 kg/m^3 to 466 kg/m^3, in most cases the strength increased to ranges of 30-50 MPa for the 28 days strength. Upon further addition of cementitious material, up to 520 kg/m^3 in some of the trial mixes, a decline in strength was noted. Thus, an optimum value for fly ash concrete mixes was taken as 466 kg/m^3. For the control mix with no fly ash, on the other hand, beyond a cementitious content of 380 kg/m^3 further addition of cementitious material did not significantly increase the 28 days strength. This value was considered as the optimum value for the control mix. Table 5.1 shows the effect of changing the cementitious content in samples containing 50% Sundance fly ash and 50% cement.

Table 5.1 Effect of the variation of Cementitious Content on Strength.

Mix	Cement (kg/m^3)	Flyash^x (kg/m^3)	Coarse Aggregates (kg/m^3)	Fine Aggregates (kg/m^3)	W/C	AEA* (ml)	S.P.$^+$ (ml)	Slump (mm)	Air Content (%)	7-Day Strength (MPa)	28-Day Strength (MPa)
15	190	190	1088	700	.28	180	1000	180	4.0	27.1	43.9
14	233	233	1088	700	.28	180	800	220	6.0	28.5	45.6
11	260	260	1088	700	.28	170	900	170	5.4	23.1	41.5

x Fly Ash: Sundance

* AEA : air entraining agent (ml/100 kg of cementitious material)

+S.P. : Superplasticizer (ml/100 kg of cementitious material)

5.1.2 Effect of Fine to Total Aggregate Ratio

The optimum value of fine to total aggregate ratio was determined by preparing and strength testing a series of trial mixes. The values for this ratio for the series of trial mixes ranged between 0.33 to 0.42. The optimum proportion of fine to total aggregate was dependant on the type of fly ash used. For Sundance, amounts of coarse aggregates used ranged from 1012 kg/m^3 to 1144 kg/m^3, and for fine aggregate, from 712 kg/m^3 to 643 kg/m^3, keeping the total amounts of aggregate at a constant level. The optimum fine to total aggregate ratio determined was 0.39 (see Table 5.2). Any deviation from this value resulted in a decline in strength of the mix. Wabamun mixes, on the other hand, resulted in very low air content. Thus, the amount of fine aggregate in the mix was decreased to achieve the target air content of 5-6%. The optimum value of fine to total aggregate ratio for Wabamun mixes was 0.37. As for Forestburg mixes, a low ratio of 0.33 resulted in an optimum value of strength with adequate workability. Table 5.2 shows the effect of varying the coarse and fine aggregate on different properties of the fresh and hardened concrete for 50% Sundance fly ash replacement.

Table 5.2 Effect of varying Fine to Total Aggregate ratio on strength.

Mix	Cement & FA * (kg/m^3)	Coarse Aggregates (kg/m^3)	Fine Aggregates (kg/m^3)	Fine to total agg.	W/C	AEA (ml)	S.P. (ml)	Slump (mm)	Air Content (%)	7-Day Strength (MPa)	28-Day Strength (MPa)
14	466	1088	700	0.39	0.28	180	800	220	6.0	28.5	45.6
27	466	1144	643	0.36	0.28	270	700	100	4.2	22.2	33.2
29	466	1037	751	0.42	0.27	340	900	170	4.6	26.9	38.2

* Cement with 50% Sundance fly ash replacement.

5.1.3 Effect of Water-Cement Ratio

Water-cement ratio is one of the most important factors affecting the strength and casting of high-strength concrete. As the water cement ratio is reduced, higher strength can be achieved. There is, nevertheless a minimum water cement ratio below which the air content and workability is drastically reduced. Superplasticizers and air-entraining agents were used to account for the loss in workability and air content. Water-cement ratios used ranged from as low as 0.27 up to 0.36. From these values, the optimum water content for different types of mixes were obtained and used to prepare the final mixes of the design. An optimum value of 0.28 was obtained for Sundance and Forestburg mixes, while a value of 0.31 was obtained for Wabamun. For the concrete mixes containing Wabamun, the water cement ratio used was higher because of the increased difficulty in achieving the desired air content with lower values. An increase in water content will facilitate the entrapment of air in the concrete mix. Table 5.3 shows the effect of changing the water cement ratio on the different properties of fresh and hardened concrete using 50% Sundance fly ash replacement. For the control mixes, a minimum water cement ratio of 0.32, (for Type I cement) and 0.36 (for type III cement) had to be used for complete hydration of the mixes.

Table 5.3 Effect of varying the Water Cement Ratio on the strength, workability and air content of concrete.

Mix	Cement (kg/m³)	Fly Ash* (kg/m³)	Coarse Aggregates (kg/m³)	Fine Aggregates (kg/m³)	W/C	AEA (ml)	S.P. (ml)	Slump (mm)	Air Content (%)	7-Day Strength (MPa)	28-Day Strength (MPa)
16	233	233	1088	700	0.27	190	800	130	3.5	31.7	42.1
42	233	233	1088	700	0.29	250	600	130	5.4	17.6	35.5
17	233	233	1088	700	0.34	170	400	195	7.0	18.9	31.4

* Sundance

5.1.4 Effect of Air-Entraining Agent

Air-entraining agent was used for all of the mixes to produce an air content of around 6%. Air-entraining agent was mixed with water for sufficient time to allow a uniform system of air bubbles to be distributed throughout the batch. The air bubbles act as a lubricant for the fine aggregates in the mix. Table 5.4 shows the effect of varying the air entraining agent on the air content using mixes containing 50% Forestburg fly ash in cementitious material. It shows that high amounts of air-entraining agent (e.g. 8%) will have detrimental effect on the strength of the mix. There was a decrease in compressive strength as more air-entraining agent was introduced to the concrete mix. Except for Wabamun mixes, the compressive strength was inversely proportional to the quantity of air-entraining agent. Air-entraining agent did not have a drastic effect on strength for Wabamun mixes. Specimens with an air content in excess of 7% to 8% showed low strength, mainly due to the low density of the mix. Table 5.4 also indicates that at higher water cement ratios, the amount of air entraining agent required is smaller for a given percentage of air entrainment.

On the other hand, air entrainment improved the workability of the mix in the plastic state. Air-entrained concrete mixes also showed less tendency for bleeding and segregation.

Table 5.4 Effect of Air-Entrainment on Strength.

Mix	Cement (kg/m³)	Fly Ash* (kg/m³)	Coarse Aggregates (kg/m³)	Fine Aggregates (kg/m³)	W/C	AEA (ml)	S.P. (ml)	Slump (mm)	Air Content (%)	7-Day Strength (MPa)	28-Day Strength (MPa)
19	233	233	1088	700	0.27	190	890	240	3.5	18.5	26.0
28	233	233	1088	700	0.27	320	1100	200	3.1	24.6	31.3
30	233	233	1088	700	0.27	380	1000	170	5.0	23.4	29.8
47	233	233	1088	700	0.29	280	1080	220	8.5	14.0	23.5

* Forestburg

5.1.5 Effect of Superplasticizer

Trial mixes with different amounts of superplasticizers were utilized to achieve good workability and adequate strength. The amount of water needed for a given workability can be reduced upon addition of a superplasticizer, thus resulting in a lower water cement ratio and a higher strength. Two types of superplasticizers were used in the trial mixes, namely, Daracem and WRDA-19. For the first five trial mixes, Daracem was used, while WRDA-19 was used for the rest of the mixes. Daracem was found to delay the setting time of the fly ash-cement paste and, therefore, it was not used after the few initial mixes. The setting time tests on the pastes were performed according to ASTM C-191 and the results are shown in Appendix B. Hereafter, in the text, the type of superplasticizer that is referred to will be WRDA-19. The Table in Appendix B also shows that the setting time increases when the amount of superplasticizer in the paste is increased.

It was noticed (see Table 5.5) that with constant water cement ratios, greater amounts of superplasticizer produced mixes with greater strength. Thus, high amounts of superplasticizers were used to achieve mixes with high strength. The amount of superplasticizer used ranged between 800-1400 ml/100 kg of cementitious material. Table 5.5 indicates that lower amounts of air entraining agents are required to obtain the same amount of air entrainment in concrete mixes containing higher amounts of superplasticizer. Large quantities of superplasticizer (greater than 1400 ml/100 kg of total cementitious material) were used for the control mixes even at high water cement ratios (greater than 0.32) because of their low workability relative to the fly ash concrete mixes.

Table 5.5 Effect of amount of superplasticizer on 7 day and 28 day strength.

Mix	Cement (kg/m^3)	Fly Ash (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	W/C	AEA (ml)	S.P. (ml)	Slump (mm)	Air Content (%)	7-Day Strength (MPa)	28-Day Strength (MPa)
70	233	233 (SD)	1088	700	.28	130	562	100	4.8	26.3	34.2
81	233	233 (SD)	1088	700	.28	130	900	140	5.3	27.9	48.2
26	233	233 (FB)	1198	590	.28	320	700	180	5.5	21.3	30.3
74	233	233 (FB)	1198	590	.28	200	1511	100	5.4	33.5	50.6
7	233	233 (WB)	1088	666	.32	170	900	180	6.6	22.3	37.1
72	233	233 (WB)	1088	666	.31	300	1437	110	5.0	34.4	48.1

SD=Sundance, WB=Wabamun, FB=Forestburg.

The amount of superplasticizer depends on the amount of fly ash utilized. The higher the percentage of fly ash in the mix, the lower the amount of superplasticizer needed to obtain a mix with similar consistency. Table 5.6 shows the amount of superplasticizer needed for different percentages of fly ash.

Table 5.6 Effect of proportion of fly ash replacement on the amount of superplasticizer.

Mix	Cement (kg/m^3)	Fly Ash* (kg/m^3)	Coarse Aggregates (kg/m^3)	Fine Aggregates (kg/m^3)	W/C	AEA (ml)	Superplast. (ml)	Slump (mm)
79	280	186	1088	700	0.28	130	1125	120
81	233	233	1088	700	0.28	130	900	140
71	186	280	1088	700	0.28	130	785	150

* Sundance

5.1.6 Effect of Set Accelerator

A set accelerator was used for some trial mixes to test its effect on setting and early strength development of concrete. Amounts of 0.5 and 1.0 kg/100 kg of cementitious material were utilized. The set accelerator had no significant impact on the strength or the setting time of concrete specimens and, therefore, further research involving set accelerators was not pursued. Larger quantities of set accelerator than those mentioned above, were not considered since the cost of using it increases the cost of the concrete mix significantly.

5.2 The Final Design Mixes

Based on the results from the trial mixes, the mix proportions for the final design mixes were decided. The proportions for the optimum design mixes are shown in Table 5.7 The mixes had a density ranging from 2167 to 2284 kg/m^3. The slump values of the design mixes varied between 100 and 170 mm with the majority falling around 130 mm. The air content of the mixes varied from 5% to 7% except in the case of the control mix with Type III cement in which the value was about 4%.

5.2.1 Slump

The results of slump tests of the different mixes are included in Table 5.7. The data shows the increased workability of concrete mixes with fly ash compared to that without fly ash for the same quantity of superplasticizers added. As a result, lower water cement ratios were attained for fly ash mixes to achieve the same slump as the control mixes. This is due to the small size and the typically spherical shape of fly ash particles which influences the rheological properties of cement pastes. This will cause a reduction in the amount of water needed for a given degree of workability relative to the equivalent paste without fly ash.

The drop of concrete during the slump test of fly ash mixes was slow and gradual in comparison with an abrupt drop for the control mixes. This indicates a sticky cohesive mix richer in fines than the control mix. The superplasticizer used was effective for 5 to 10 minutes from initial contact with the concrete. After that, there was a marked decline in the slump and a gradual stiffening of the concrete.

Wabamun mixes, on the other hand, showed lower workability than either Forestburg or Sundance mixes, but still showed better workability than the control mix. This is because of the relatively coarser particles of the raw Wabamun fly ash. In general, use of fly ash in concrete has produced better workability with a marked improvement in the finish of the concrete mix.

5.2.2 Air Entrainment Test Results

Air entraining agent was added with the water during mixing to obtain the desired number of correctly spaced air voids that are essential for good durability to freeze and thaw in the hardened concrete. The data for air content is included in Table 5.7.

The results showed an increase in demand for air-entraining agent for mixes with fly ash compared to the control mix to achieve an air content of around 6%. The demand was more pronounced in raw Wabamun fly ash mixes. The amount required for Wabamun was two to three times as much as either Sundance mixes or Forestburg mixes. This is most true for 60% Wabamun fly ash as replacement of cement. Sundance mixes, on the other hand, required the least amounts of air-entraining agent among the different fly ashes used, but slightly more than that of the control mix.

In general, air content of around 6% could be achieved for all fly ash mixes but with an increase in the amount of air-entraining agent added. Generally, the mixes containing fly ash required 2 to 3 times more air-entraining agent as compared to the control mix.

Table 5.7 Properties of Fresh Concrete for Final Design Mixes.

Mix	Fly Ash⁺ (kg/m³)	Cement (kg/m³)	Coarse Aggregate (kg/m³)	Fine Aggregate (kg/m³)	W/C	AEA (ml)	Superplasticizer (ml)	Density (kg/m³)	Slump (mm)	Air Content (%)
79	186 (SD)	280 (I)	1088	700	0.28	130	1125	2258	120	5.2
81	233 (SD)	233 (I)	1088	700	0.28	130	900	2206	140	5.3
71	280 (SD)	186 (I)	1088	700	0.28	130	785	2206	150	5.2
77	233 (SD)	233 (III)	1088	700	0.28	130	1429	2175	110	6.8
82	186 (WB)	280 (I)	1088	666	0.31	300	1000	2206	125	5.7
72	233 (WB)	233 (I)	1088	666	0.31	300	1437	2311	110	5.0
73	280 (WB)	186 (I)	1088	666	0.32	450	1250	2284	150	6.0
80	186 (FB)	280 (I)	1198	590	0.28	150	1083	2167	130	7.0
74	233 (FB)	233 (I)	1198	590	0.28	200	1511	2208	100	5.4
75	280 (FB)	186 (I)	1198	590	0.28	150	1408	2167	150	6.0
78	********	380 (III)	1088	700	0.36	100	2500	2285	170	4.3
76	********	380 (I)	1088	700	0.32	70	1406	2285	100	5.0

+ SD = Sundance, WB = Wabamun, FB = Forestburg

5.2.3 Initial and Final Setting Time Results

The setting time test was performed for all of the design mixes to monitor the initial and final set of the mix. The setting time test provides information on the early strength development of the concrete and the time when the concrete mix will become more stiff and, as a result, less workable. The results of the setting time are given in Table 5.8.

Fly ash, as shown in Table 5.8, had a retarding effect on the setting of the concrete mix. Concrete specimens without fly ash reached an initial set of five hours at an ambient air temperature of about 15°C. However, the fly ash mixes achieved an initial set of 8 to 11 hours. This can be attributed to the slow pozzolanic reactions that occur between fly ash and CaO in the cement. The final set for fly ash mixes ranged from 10 to 13 hours, while for control mixes it was achieved in 7 hours. It was noted from the setting time test that most of the specimens achieved final set 2 to 3 hours after initial set.

The setting time of fly ash concrete mixes varied depending on the amount of fly ash present and the type of fly ash used. The initial set increased from 8 hours, for a mix of 50% Sundance fly ash and 50% cement, to 11 hours, for a mix of 60% Sundance and 40% cement as cementitious material. This type of behavior was observed for most of the mixes where higher proportions of fly ash was introduced into the concrete. The setting time varied also according to the type of fly ash utilized, although the variation was not very pronounced. The setting times for Wabamun fly ash concrete mixes were shorter than those of either Forestburg or Sundance. Among the mixes with 50% fly ash replacing cement, the initial setting time recorded for Wabamun fly ash concrete mix was 7 1/2 hours in comparison with 8 and 9 1/2 hours for Sundance and Forestburg fly ash concrete mixes, respectively.

High early strength cement (Type III) was also utilized with 50% Sundance replacing cement to monitor the effect of cement type on setting time. The value of the inital set obtained did not change significantly when Type III cement was used in place of Type I cement. The control mix with Type III cement instead of Type I cement also showed no considerable difference in the setting time of the concrete. A set accelerator was utilized for some trial mixes to study its effect on setting time and early strength development. This accelerator was used at dosages of 0.5 and 1.0 kg/100kg of cementitious material and proved ineffective in reducing the setting time of the fly ash specimens. Dosages higher than 1.0 kg/100 kg of cementitious material were not tried due to cost considerations.

During the setting time test, the amount of water bleeding from the specimen was observed. It was noted that fly ash mixes showed reduced bleeding and segregation relative to the control mix.

Table 5.8 Initial and Final Setting Times of Final Design Mixes

Mix	Fly Ash Type & % Replacement by weight of cement	Initial Setting Time (Hrs.)	Final Setting Time (Hrs.)
81	Sundance, 50% (Type I)	8.0	10.5
71	Sundance, 60% (Type I)	11.0	13.0
79	Sundance, 40% (Type I)	10.0	12.0
77	Sundance, 50% (Type III)	9.0	12.0
72	Wabamun, 50% (Type I)	7.5	9.5
73	Wabamun, 60% (Type I)	9.0	10.5
82	Wabamun, 40% (Type I)	7.0	9.5
74	Forestburg, 50% (Type I)	9.5	12.0
75	Forestburg, 60% (Type I)	11.0	13.5
80	Forestburg, 40% (Type I)	8.5	10.0
76	Control Type I	4.5	6.5
78	Control Type III	5.5	7.0

5.2.4 Compressive Strength Test Results

Compressive strength tests were performed on the specimens from the design mixes at the ages of 1, 3, 7, 28, 56, 120 days. The specimens were stored in an environment of 100 % relative humidity until they were tested. Each compressive strength value, shown in Table 5.9, represents the average of three strength values.

The fly ash concrete mixes attained slightly lower strengths than the control mix with no fly ash, but, nevertheless, the target 28 day strength of 45-60 MPa was met for most of the mixes. The exceptions to the above strength requirement were concrete mixes with 60% Sundance, 60 % Wabamun, and 40% Forestburg replacing cement, with the 28 day compressive strength being 41.5, 37.6, and 42.1 MPa, respectively. The control mix acquired a 28 day compressive strength of 53.9 MPa. As expected, the rate of strength development for concrete with fly ash was slower than that of the control mix. After one day, the compressive strength of the control mix reached 34.3 MPa, while for the mixes with 40%, 50%, and 60% fly ash replacing cement, the ranges of strength attained, for the different types of fly ashes, were between 14-20, 10-16, and 7-11 MPa, respectively. After three days, the fly ash mixes developed strengths in the order of 25-29 MPa for 40% fly ash, 23-26 MPa for 50% fly ash, and 10-16 MPa for 60% fly ash replacing cement. Therefore, strength development after three days in mixes with 40% and 50% fly ash is within the range of normal concrete.

The compressive strength of the fly ash mixes was dependant on several factors such as the amount of fly ash used, the amount of superplasticizer and air-entraining agent used. It was noted that the amount of superplasticizer added to concrete during mixing had an impact on strength of concrete specimens. As the amount of superplasticizer added was increased, the strength improved, especially after 28 days. A 40.9 % increase in strength was achieved from a value of 34.2 MPa (mix #70) to a value of 48.2 MPa (mix #81) for 50% Sundance and 50% cement mix when the amount of superplasticizer added increased from 562 to 900 ml/100 kg of

Table 5.9 Compressive Strengths for Final Design mixes at 1, 3, 7, 28, 56, 120 days.

MIX #	Fly Ash Type & % Replacement by weight of cement	DAY-1 (MPa)	DAY-3 (MPa)	DAY-7 (MPa)	DAY-28 (MPa)	DAY-56 (MPa)	DAY-120 (MPa)
81	Sundance, 50% (Type I)$^+$	11.3	23.2	27.9	48.2	51.6	61.5
71	Sundance, 60% (Type I)	9.6	13.7	25.5	41.5	44.4	60.7
79	Sundance, 40% (Type I)	16.3	28.6	39.8	47.0	57.8	69.3
77	Sundance, 50% (Type III)	15.4	31.6	41.0	49.9	58.6	67.1
72	Wabamun, 50% (Type I)	16.0	26.0	34.4	48.1	54.0	74.6
73	Wabamun, 60% (Type I)	7.6	14.4	21.9	37.6	42.5	60.7
82	Wabamun, 40% (Type I)	19.9	26.8	34.3	50.7	49.1	72.4
74	Forestburg, 50% (Type I)	11.1	26.3	33.5	49.6	54.2	66.8
75	Forestburg, 60% (Type I)	10.6	16.8	24.6	43.4	46.4	61.2
80	Forestburg, 40% (Type I)	13.8	25.4	29.6	42.1	43.4	54.8
76	Control Type I	34.3	35.3	46.8	53.9	57.7	74.6
78	Control Type III	36.2	42.8	44.1	58.7	59.2	76.4

+ Cement type used.

cementitious material. The difference in strength between the two mixes can be clearly seen from Fig 5.1. High amounts of superplasticizer were added to the final mixes.

Figs. 5.1, 5.2 and 5.3 show the strength development with time for concrete mixes with fly ash types Sundance, Wabamun and Foresturg, respectively. The effect of the amount of fly ash in the mix on strength can, also, be seen from these figures. The strength data indicates that the control mix with no fly ash has the highest strength at all ages when compared with the mixes containing fly ash. However, the strength values, at and beyond 56 days, for the mixes with 40% Sundance, 40% Wabamun, 50% Wabamun, and 50% Forestburg replacing cement are very similar to the strength values of the control mix. Fig 5.1 indicates that the strength values of the mixes containing 50% and 60% replacement of cement by Sundance are lower than the mix with 40% for the same fly ash. Fig 5.2 shows that mixes with 40% and 50% Wabamun have similar strength values, while the mix with 60% Wabamun replacing cement has lower strength. From Fig 5.3, it is evident that the mix with 50% Forestburg in the cement content possesses greater strength than the mixes with 40% and 60% of the same fly ash.

Figs. 5.4, 5.5 and 5.6 compare the strength of the different mixes containing 40%, 50% and 60% fly ash, respectively, in place of cement. Of the mixes with 40% fly ash in the total cement content, the ones containing Wabamun and Sundance had greater strength than the mix with Forestburg (see Fig 5.4). In the case of mixes containing 50% cement replacement by fly ash, all three fly ash types had similar strength results at all times, with the exception of the mix with Wabamun at 120 days, whose strength was greater than the other two fly ash concrete mixes (Fig 5.5). Fig 5.6 shows that the type of fly ash does not have a significant effect on strength for mixes containing 60% fly ash as cementitious material.

Use of Type III cement in place of the normal Type I increases the strength of the concrete mixes as shown in Fig 5.7. The strength increase, however, is very small particularly at later ages.

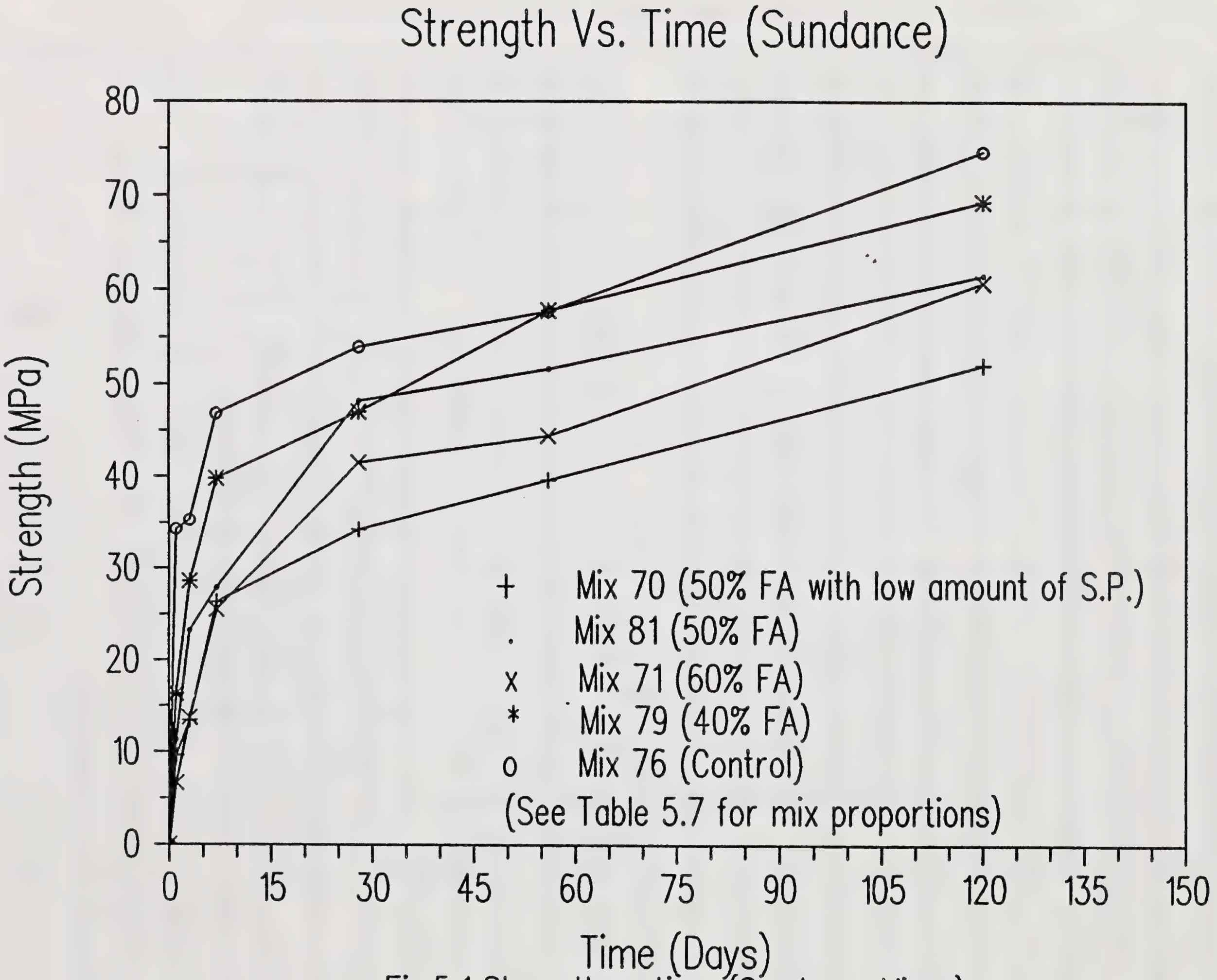

Fig.5.1 Strength vs time (Sundance Mixes)

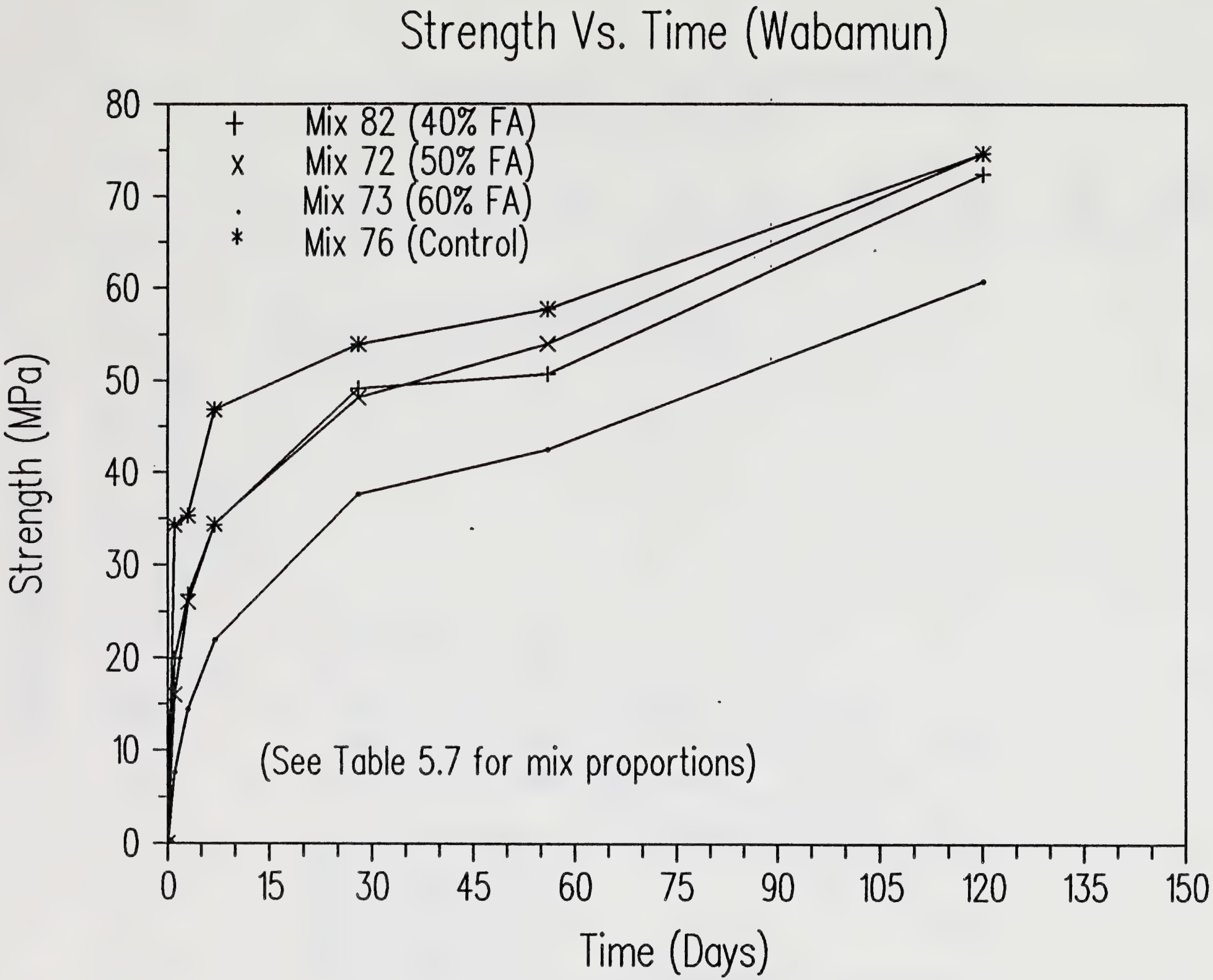

Fig.5.2 Strength vs time (Wabamun mixes)

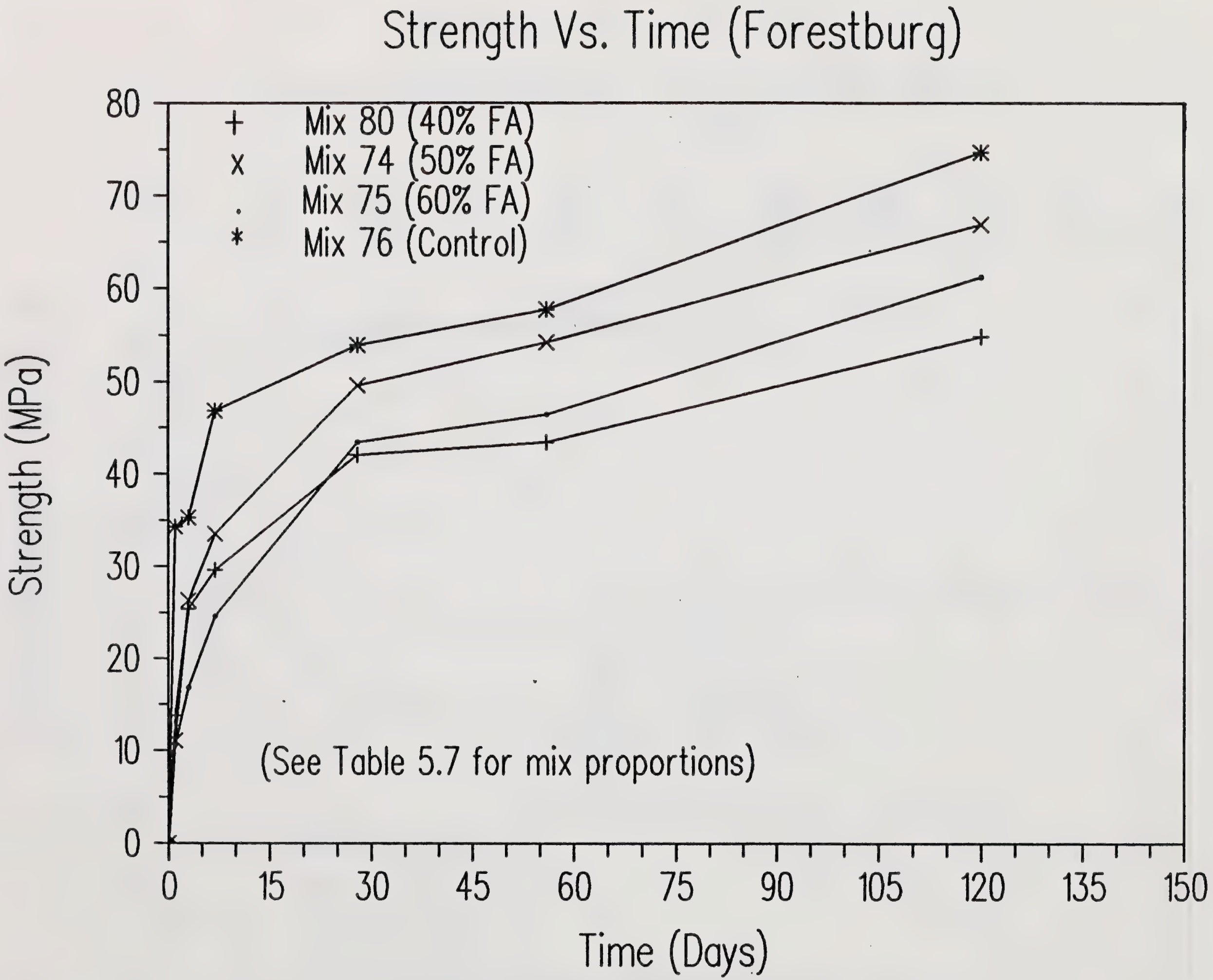

Fig.5.3 Strength vs time (Forestburg mixes)

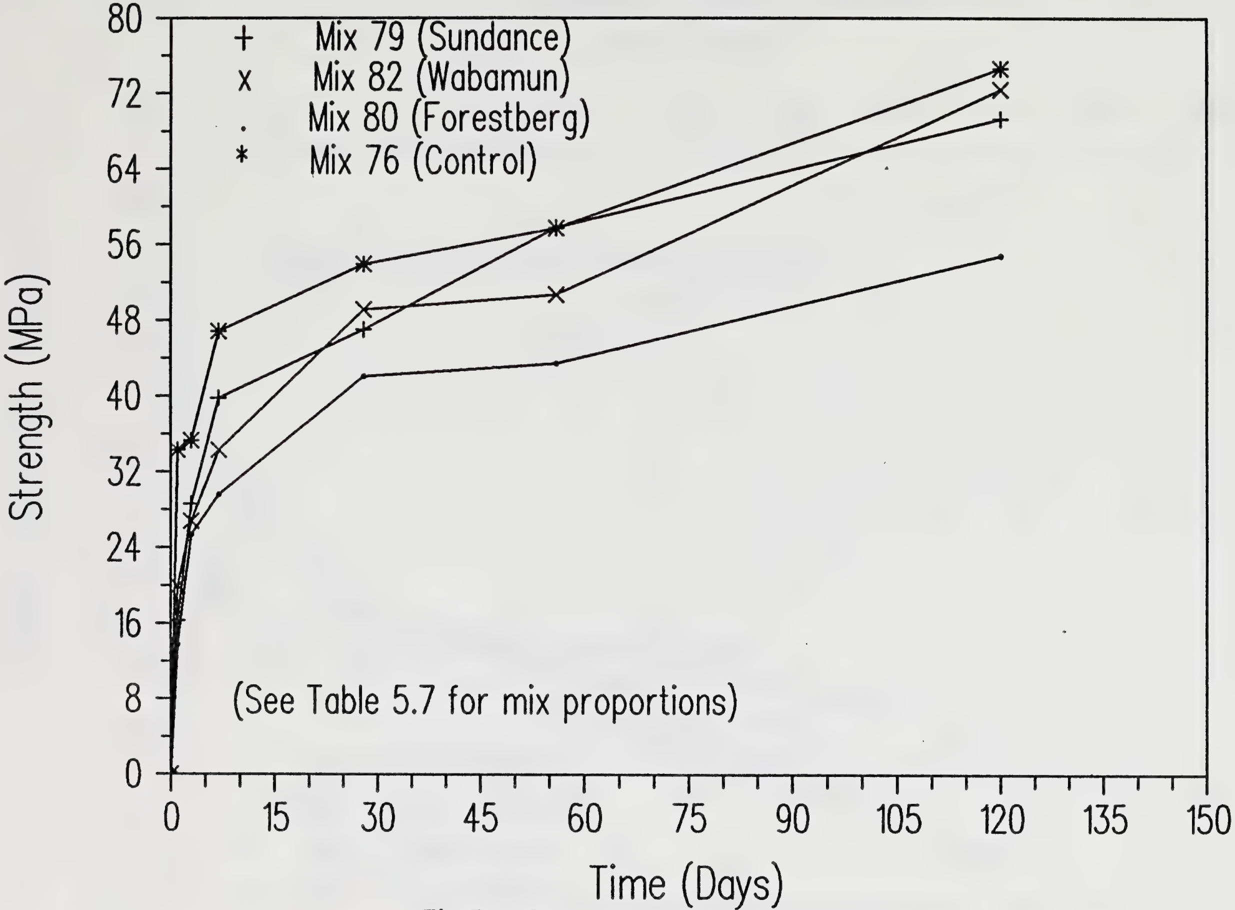

Fig.5.4 Strength of 40% fly ash mixes

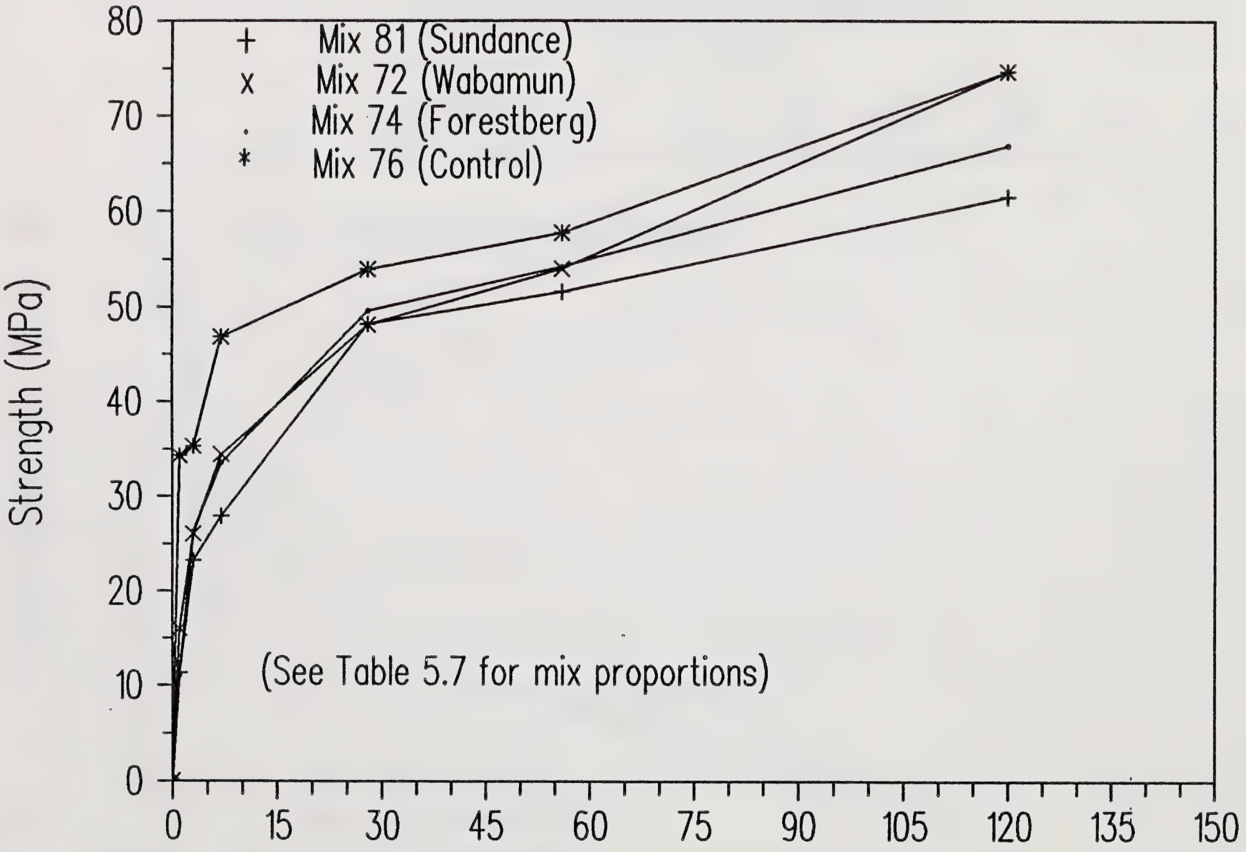

Fig.5.5 Strength of 50% fly ash mixes

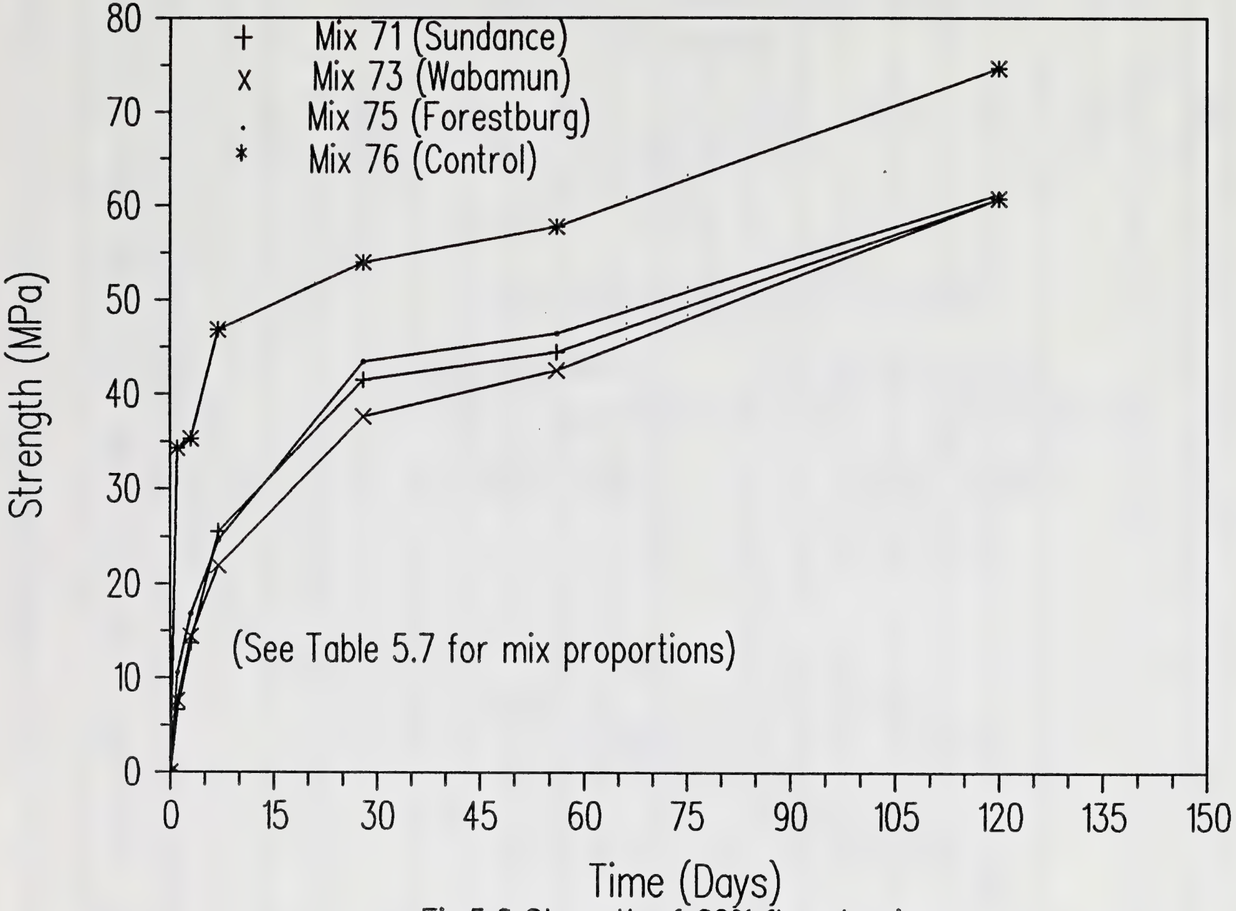

Fig.5.6 Strength of 60% fly ash mixes

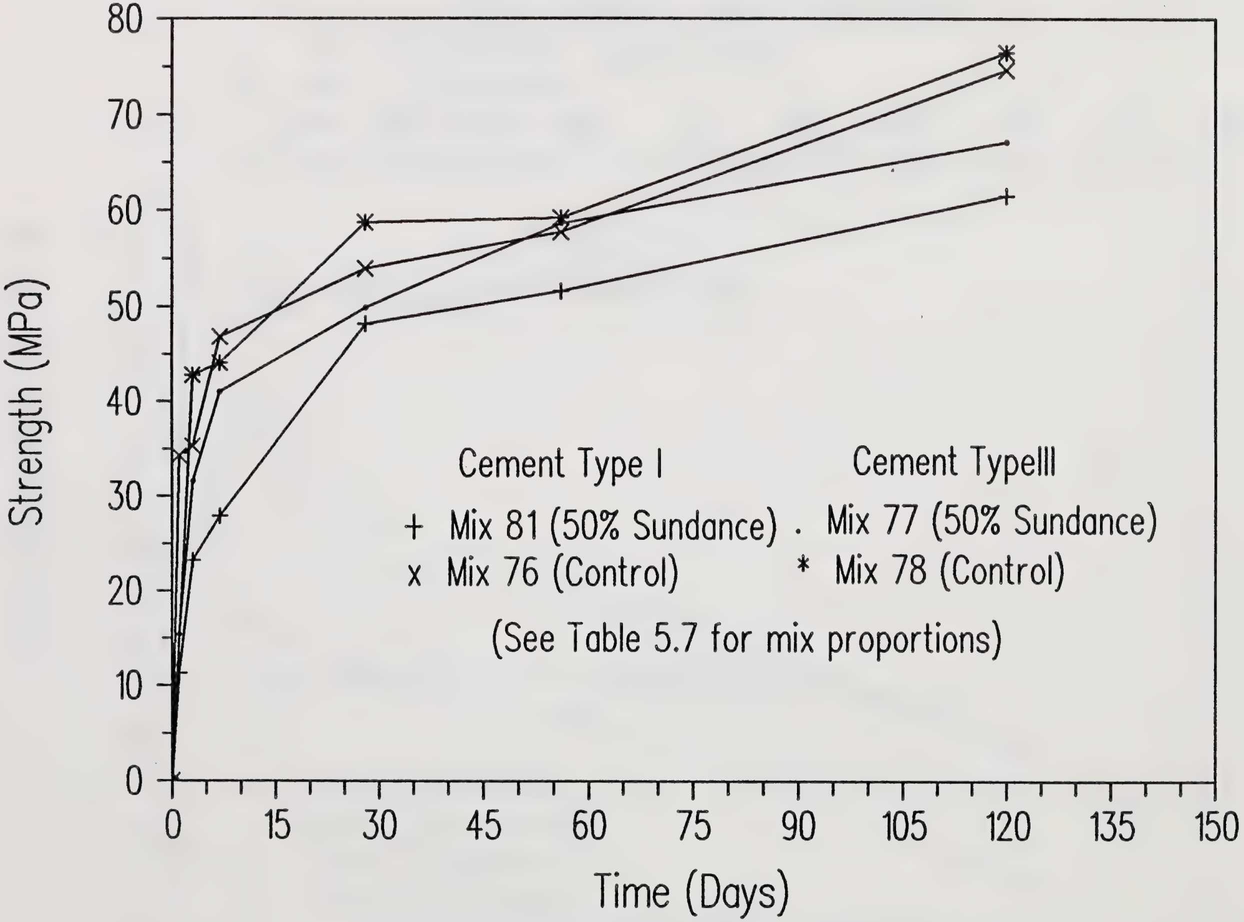

Fig.5.7 Strength of cement types I and III mixes

5.2.5 Freeze and Thaw Test Results

Tests to determine the freeze and thaw resistance were carried out on all of the final design mixes using ASTM C666-Procedure A. These tests were conducted on specimens which were moist cured for 14 days. The tests were terminated after 300 freeze-thaw cycles or when the relative dynamic modulus fell below 60% of initial, whichever occurred first. The test results are based on an average value of three specimens.

Most of the fly ash concrete samples possessed high durability to freeze and thaw action. The majority of the specimens tested had a dynamic modulus of elasticity of greater than 60% at 300 cycles with the exception of specimens from three mixes (see Figs 5.8 to 5.11). The control mix with high early cement (Type III) had a low level of durability of 53% after 278 cycles. The other two mixes that failed the durability test were those containing 50% Wabamun and 50% Sundance fly ash in cementitious material. They had a dynamic modulus of 37% at 254 cycles and 55% at 300 cycles, respectively.

The majority of the fly ash concrete specimens achieved adequate durability in excess of 76% after 300 cycles. The control mix with normal Type I cement, on the other hand, exhibited no change in the dynamic modulus of elasticity even after 303 cycles. In all of the cases where the dynamic modulus was below 60% prior to the completion of 300 freeze-thaw cycles (mix nos. 78, 70, and 72), it was noted that the air content ranged between 4.3% to 5.0%. Mixes with an air content of greater than 5% had high durability against freeze-thaw action.

As indicated in the literature, concrete mixes must be relatively impervious to allow for proper resistance to freeze-thaw cycles in cold regions. The literature also indicates that the permeability of concrete mixes containing high amounts of fly ash decreases with time. Therefore, freeze thaw durability of high fly ash concrete can be expected to increase with time because of the decrease in permeability. The specimens that were used for the freeze-thaw durability tests in this study were only 14 days of age at the beginning and less than three months old by the time the tests

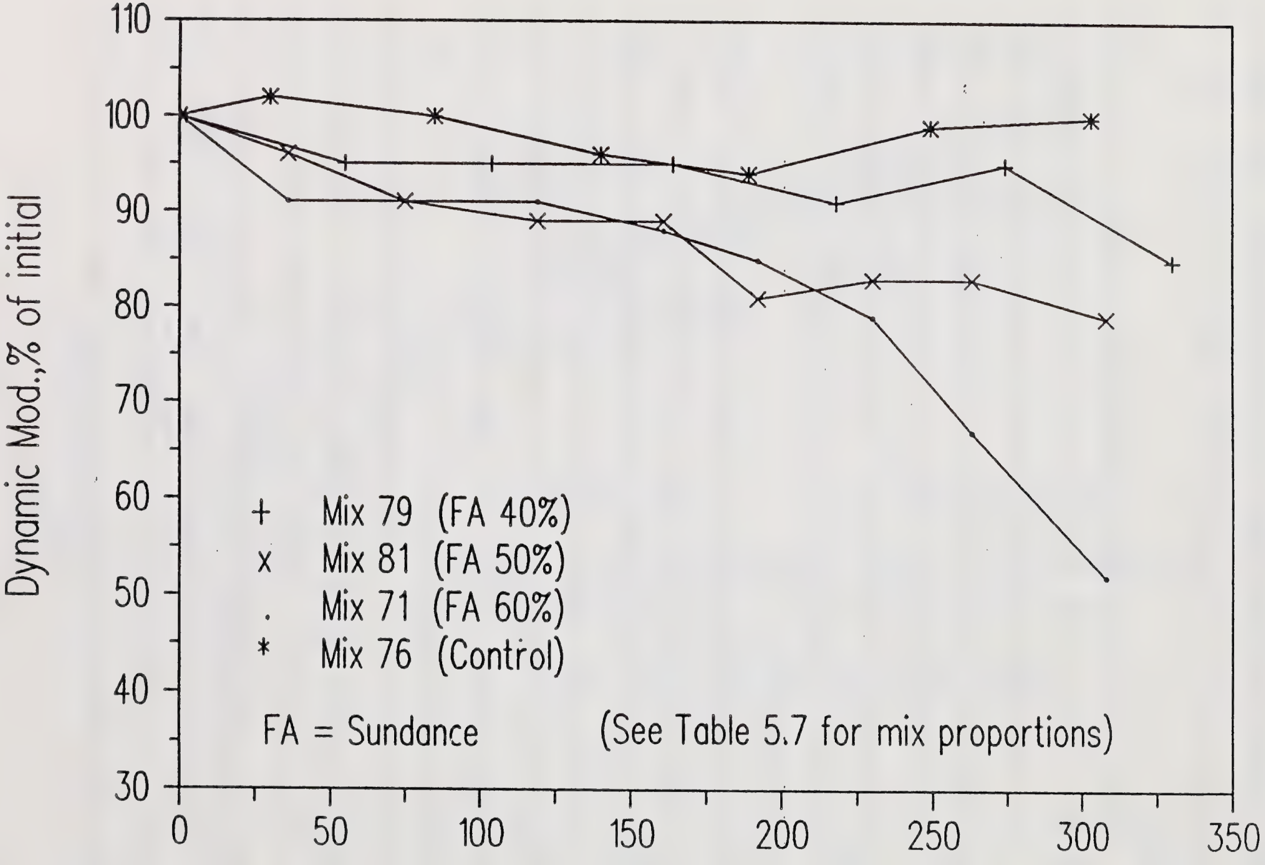

Fig.5.8 Dynamic moduli for Sundance mixes

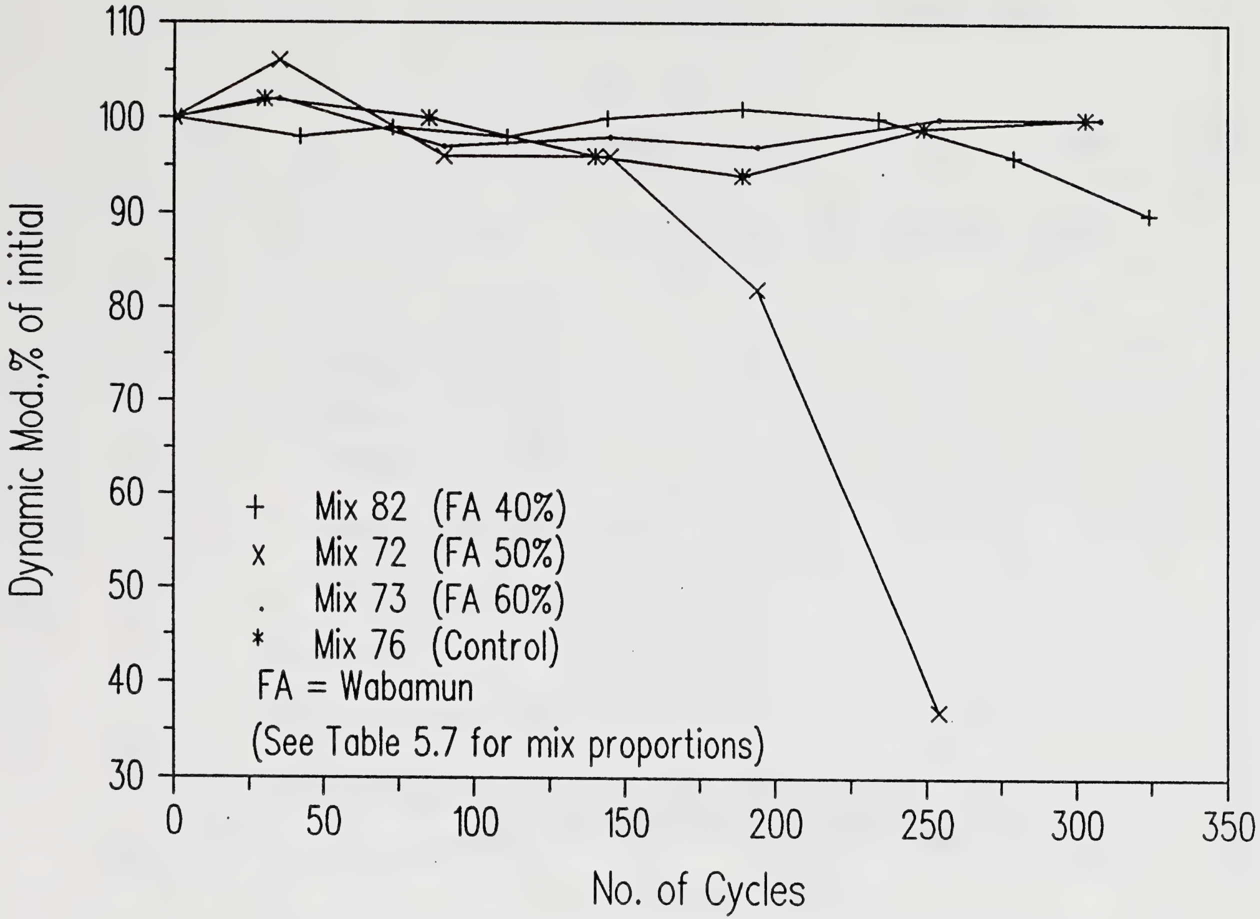

Fig.5.9 Dynamic moduli for Wabamun mixes

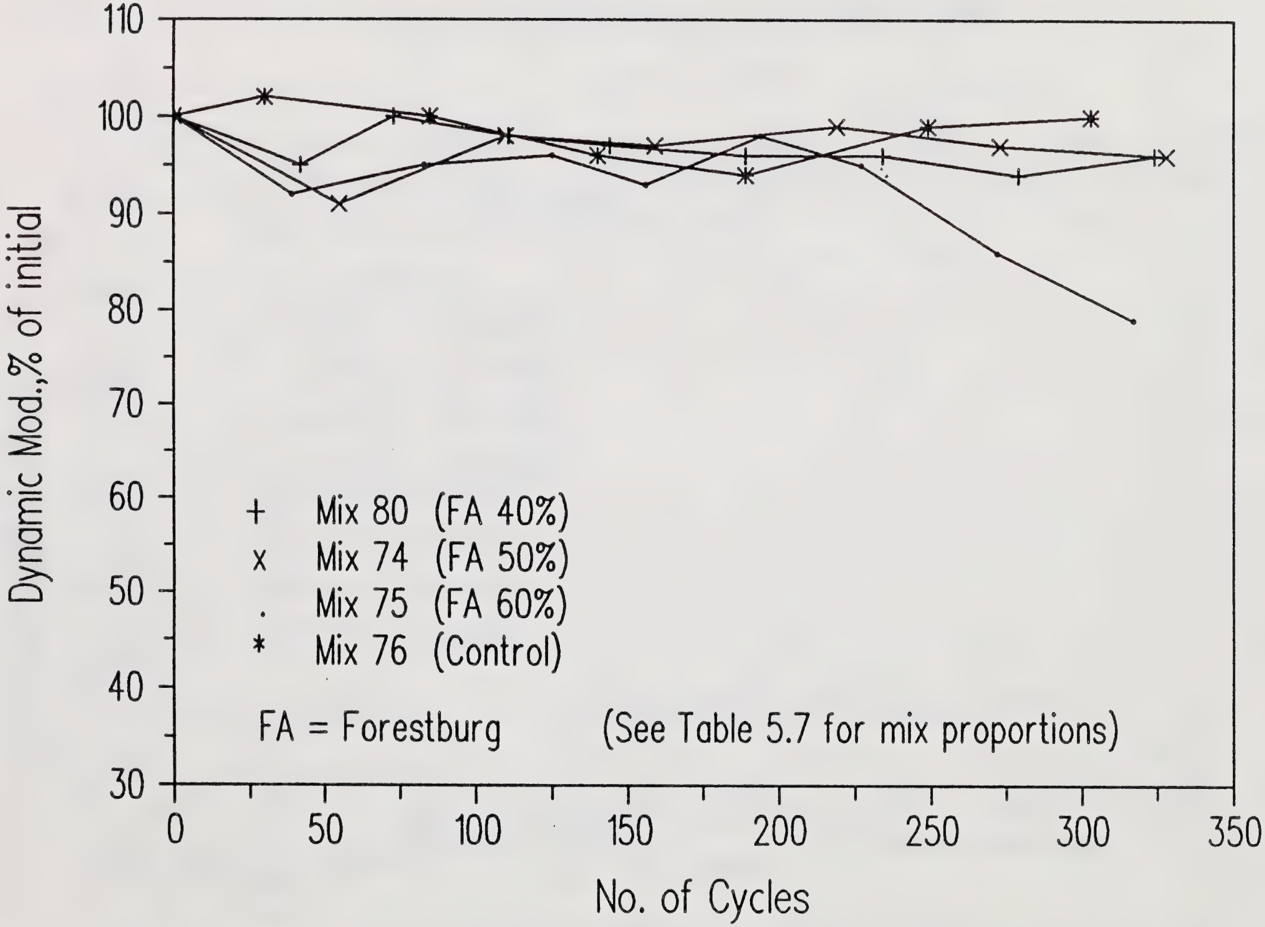

Fig.5.10 Dynamic moduli for Forestburg mixes

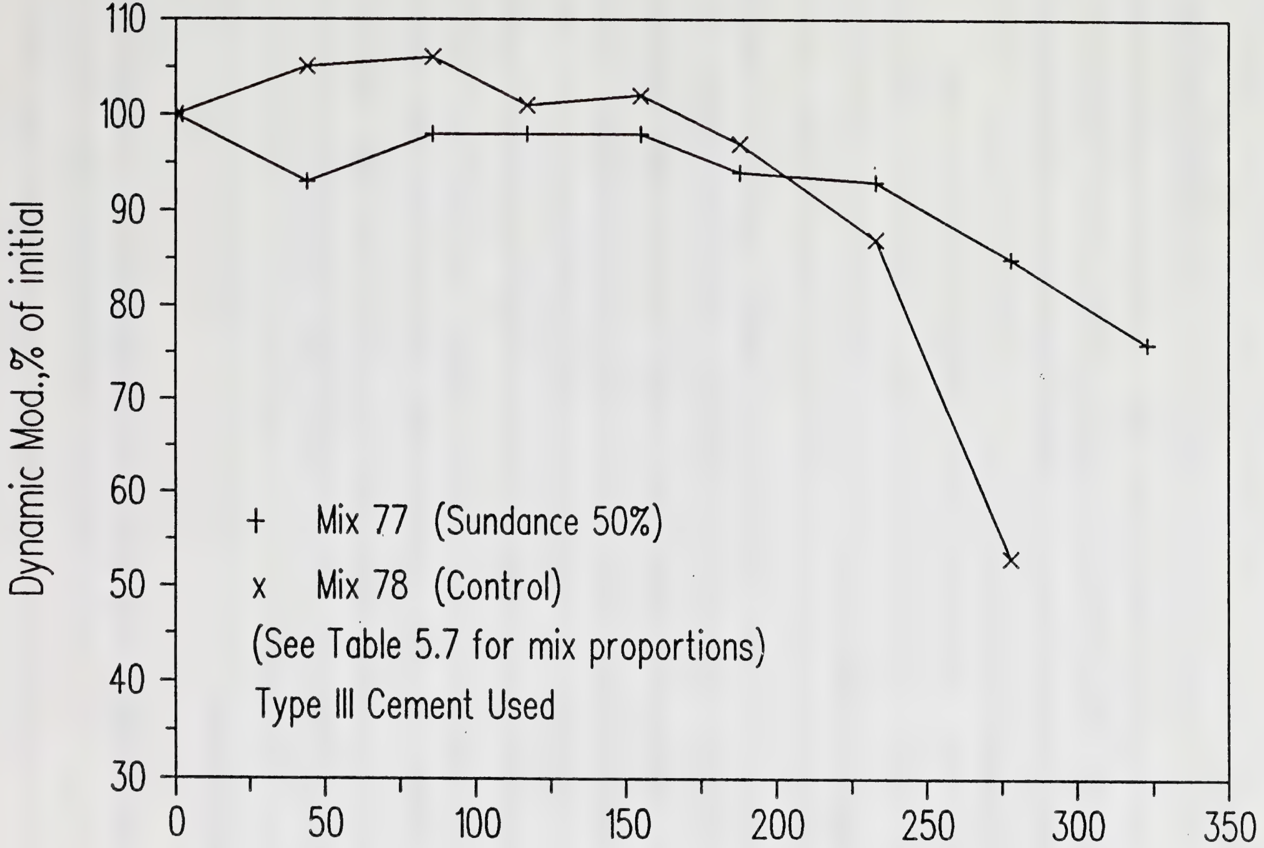

Fig.5.11 Dynamic moduli for Type III cement mixes

were completed after 300 freeze-thaw cycles. Some of the specimens that failed under the rapid freeze-thaw action would probably pass the durability test if the freeze thaw cycles were repeated at a slower pace and if the concrete specimens were given ample curing time in excess of 14 days prior to testing so that they could develop lower permeability.

All of the concrete specimens subjected to freeze-thaw durability tests, including those from control mixes, showed slight to moderate scaling after 200-250 freeze-thaw cycles and exhibited some weight loss towards the end of the test. The weight loss recorded for the concrete specimens after 300 freeze-thaw cycles was around 0.5% and less in all cases.

5.2.6 Resistance to Sulphate Attack

Resistance to sulphate attack is one of the important aspects of the behavior of fly ash in concrete. Alberta fly ashes replacing cement have been, already, tested for sulphate resistance in a previous study by Day and Joshi (1986). Therefore, further testing on sulphate resistance was not performed in this program. The main conclusions extracted from the above publication are presented below.

Replacement of 50% cement by Alberta fly ashes improved the sulphate resistance of sand-cement mortars. All the mortars containing fly ash showed adequate resistance to a suphate environment for over a year with minimal expansions. As the pH was allowed to decrease, the mixes showed small expansions, in comparison with the control mix which achieved high expansions over time.

5.2.7 Drying Shrinkage

Drying shrinkage of high fly ash (from Alberta) concrete has been already studied by Haque et al. (1984). Therefore, no further tests were conducted to determine the drying shrinkage of the concrete mixes developed in this research.

Tests conducted by Haque et al. on concrete with 40% to 75% cement replaced by fly ash indicated that drying shrinkage of concrete decreased with increase in fly ash content. Lower temperature rise during hydration compared to conventional concrete mixes makes high fly ash concrete less susceptible to shrinkage cracks.

5.3 Economic Evaluation

Increases in energy costs to manufacture portland cement, the depletion of high quality natural material and the problem of ultimate disposal of the fly ash, have led to the increased use of fly ash in various applications in the concrete industry.

The use of fly ash, in general, leads to a reduction of production costs and improvement in the properties of fresh and hardened concrete (Hanson, 1986). The cost of fly ash concrete will usually vary with the source of supply, price and quality of fly ash, and the transportation cost of fly ash from the power plant to the batching site.

In the present study the costs of fly ash and cement were obtained for four locations in Alberta, namely, Edmonton, Calgary, Lethbridge, and Peace River. The latter two cities were chosen since they are located close to the south and north ends of the province, respectively. This should provide a better idea of the change in prices of the concrete mixes from place to place within the province. Based on the cost of raw materials, the cost of producing a cubic meter of concrete was determined for each of the final design mixes (see Appendix C). The results of the economic evaluation are presented in Table 5.10 . The data in Table 5.10 show that the costs of producing concrete mixes with 40% to 60% cement replacement are lower than that of the control mix with portland cement type I and high early strength cement type III. The savings, based on the price of control mix, increase with an increase in the amount of cement replacement by fly ash. Thus, when using Sundance fly ash in the Edmonton area, the savings increase from 8.3% to 21.3% when the amount of fly ash in concrete increases from 40% to 60%.

Table 5.10 Cost of Fly Ash Concrete for different locations in Alberta.

Mix No.	Fly Ash (%) Replacement	Cost for Edmonton			Cost for Calgary			Cost for Lethbridge			Cost for Peace River		
		Fly Ash $/tonne	Concrete $/m³	Savings %	Fly Ash $/tonne	Concrete $/m³	Savings %	Fly Ash $/tonne	Concrete $/m³	Savings %	Fly Ash $/tonne	Concrete $/m³	Savings %
79	40 (SD)	43	68	8.3	58	68	4.0	68	69	1.0	67	80	5.0
81	50 (SD)	43	61	16.1	58	64	9.7	68	66	5.9	67	74	11.2
71	60 (SD)	43	57	21.3	58	61	14.9	68	63	10.3	67	69	17.0
77^+	50 (SD)	43	63	12.8	58	66	7.4	68	68	3.6	67	76	8.7
82	40 (WB)	36	65	10.6	51	67	6.3	61	68	3.4	60	78	7.0
72	50 (WB)	36	62	15.0	51	64	9.6	61	66	5.9	60	74	11.1
73	60 (WB)	36	57	21.7	51	60	15.2	61	63	10.7	60	69	17.1
80	40 (FB)	40	66	9.6	50	67	6.5	70	69	0.9	75	81	3.6
74	50 (FB)	40	63	13.6	50	64	9.8	70	68	2.7	75	78	6.7
75	60 (FB)	40	58	20.3	50	60	15.6	70	65	7.0	75	74	12.1
76	0	--	73	--	--	71	--	--	70	--	--	84	--
78^+	0	--	76	--	--	75	--	--	74	--	--	87	--

+ Cement Type III

Wabamun fly ash mixes resulted in the maximum savings due to the reduced cost of the raw ash. The cost of unclassified Wabamun fly ash was estimated as $ 7 less than that of classified Sundance ash. The amount of Wabamun fly ash produced, however, is considerably lower than that of Sundance and this might affect its availability. The amount of Wabamun fly ash produced is about 50% of the amount of Sundance fly ash produced annually. Forestburg fly ash mixes also showed savings comparable to Wabamun fly ash mixes depending on the amount of fly ash used and the location in Alberta.

The cost savings are highest in Edmonton and Peace River due to the low cost of fly ash in Edmonton and the high cost of cement in Peace River. In the Calgary area, the highest savings recorded correspond to the mix containing 60% Forestburg fly ash in place of cement due to the lower cost of the ash compared to other fly ashes in this location. The savings, however, are lower compared to those of fly ash concrete in Edmonton due to the increase in transportantion cost of fly ash for Calgary. The same is true for Lethbridge where fly ash costs around $20 more than for Edmonton causing a reduction in cost savings. The lower costs of cement in Lethbridge also correspond to lower cost savings of 10.3%, 10.7%, and 7.0% for Sundance, Wabamun, and Forestburg mixes, respectively. In Peace River, the high cost of cement gives rise to better savings of up to 17.0% for the high fly ash concrete mix with 60% Sundance fly ash. These results from the economic analysis are valid only for the province of Alberta and any generalization might be misleading and inaccurate.

According to Mehta (1978), the manufacture of 1 ton of portland cement in the United States requires fossil fuel input of the order of 7805.4 MJ (7.4 million Btu). Since fly ash normally does not need additional energy input before use, it is clear that the savings in energy from cement replacement by such an admixture in concrete would be very high. Lane and Best (1982) have convincingly demonstrated the economic benefits from the use of fly ash as a mineral admixture in concrete. As an example, they cited that for 72,000 m^3 of concrete placed at Normandy Dam, 10,000 tons of fly ash were required resulting in a cement reduction of 6600 tons and a cost saving of \$ 225,000. Again at the Watts Bar Nuclear Plant, an estimated 244,800 m^3 (320,000 yd^3) of structural and mass concrete containing fly ash have resulted in savings of \$ 825,000 over conventional concrete. The savings for structural concrete and mass concrete were \$2.29/m^3 (\$1.75/yd^3) and \$2.61/m^3 (\$2.0/yd^3), respectively, from the use of fly ash. The indirect conservation of energy and natural resources is an added benefit in all such cases.

The present study further demonstrates the significant economic benefits of using high amounts of fly ash as partial replacement of cement in the development of high strength concrete mixes.

5.4 Possible Applications of the High Fly Ash Concrete Mixes

In Chapter 3 the specific applications of high fly ash concrete mixes, as described in the literature, were outlined. Based on this information, along with the results obtained from this study the suitability of using the mixes developed in this research program for particular applications can be discussed as follows.

Construction of structural elements in buildings such as slabs, beams, columns and foundations, in some occasions, require high strength concrete. The following high fly ash concrete mixes (Group A) designed in the present study may be used in these instances.

Group A Mixes

Mix 74: 50% Forestburg replacing cement (Type I)
Mix 77: 50% Sundance replacing cement (Type III)
Mix 79: 40% Sundance replacing cement (Type I)
Mix 81: 50% Sundance replacing cement (Type I)
Mix 82: 40% Wabamun replacing cement (Type I)

The mix proportions for the above concrete mixes are given in Table 5.7. As reported in section 5.2.3, the 28 day compressive strength of these mixes exceeds 45

MPa, while the 3 day strength is around 25 MPa, and more, which is similar to the strength of normal concrete. Furthermore, the setting times (both initial and final) of the mixes are only delayed by 5 hours or less compared to the control mix with no fly ash. The initial strength development of the fly ash concrete mixes can, therefore, be considered to be adequate for most of the cases in building construction. The delay in the setting times obtained in this study are much smaller than those reported by others (eg. greater than 14 hours of delay in the initial setting time reported by Rodway et al., 1985) for high fly ash concrete.

All the mixes in group A have high workability (with slump values ranging between 110 and 140 mm) and high durability characteristics. High workability characteristics of high fly ash concrete mixes will allow their use in heavily reinforced structural elements. The advantages of using the mixes in group A over conventional concrete mixes with no fly ash for the specific applications outlined above can be summarized as;

- reduced material and construction cost,
- better durability characteristics,
- lower permeability,
- lower drying shrinkage,
- lower temperature rise during hydration making the concrete less susceptible to shrinkage cracks.

The following concrete mixes (Group B) developed in this study have lower strengths and rates of initial strength development compared to the mixes in group A.

Group B Mixes

Mix 71: 60% Sundance fly ash replacing cement (Type I)
Mix 73: 60% Wabamun fly ash replacing cement (Type I)
Mix 75: 60% Forestburg fly ash replacing cement (Type I)
Mix 80: 40% Forestburg fly ash replacing cement (Type I)

Although the 28 day compressive strength values of the above fly ash mixes ranged from 35 to 45 MPa, the 3 day strengths were much lower, ranging between 14 and 25 MPa. Delay in the setting times by about 7 hours or less were observed for these mixes also.

When the 28 day strength values are considered, the mixes in group B still fall in the category of high strength concrete. Furthermore, except for mix # 71, all the other three mixes had high freeze-thaw resistance. Mix # 71, on the other hand, indicated marginal freeze-thaw resistance. Like the mixes in group A, group B mixes have high workability characteristics (with slump values ranging between 130 and 150 mm) and are also likely to possess other properties such as low permeability, shrinkage etc. that are inherent to high fly ash concrete mixes.

The high fly ash concrete mixes in group B may be used in the construction of structural elements (eg. slabs, beams, foundations, etc.) that do not require fast strength development initially for the purpose of rapid construction. These mixes may be also used in the construction of roadways, sidewalks and in curb and gutter construction. Lower costs, low permeability and shrinkage characteristics, and less susceptibility to shrinkage cracks are some of the advantages of using these mixes over the conventional concrete mixes with no fly ash. High fly ash concrete mixes can be used, particularly, for floor slabs and walls in conventional basements which require low permeability concrete mixes that will develop very little or no shrinkage cracks.

However, when using high fly ash concrete mixes in cold temperature conditions proper curing is important, particularly during early stages in order to minimize the lower rate of strength development (see Chapter 3). Curing periods similar to those used for normal construction should be adequate for high fly ash concrete mixes.

6. CONCLUSIONS

Based on the results of this study, in which concrete mixes containing up to 60% fly ash as replacement for cement were tested, the following conclusions can be made.

1. Fly ash reacts as a pozzolan to form cementitious hydrates. As a result of the slow pozzolanic reaction, longer setting time is required for the mixes with high percentages of fly ash. The initial setting time of the high fly ash concrete mixes ranged between 8 and 11 hours compared to 5 hours for the control mix containing no fly ash. The final setting time for the fly ash mixes varied between 10 and 13 hours while for the control mix it was 7 hours. The slight delay in setting time due to the introduction of fly ash in the design concrete mixes may not cause significant problems in the field unless rapid construction is warranted on a particular project. In residential housing development, delayed setting time may not be of great significance.
2. Bleeding and segregation are reduced because of the introduction of fly ash in concrete.
3. Fly ash in fresh concrete acts as a fine aggregate thus imparting more workability to the mix. In these mixes, lower water cement ratios can be used for fly ash mixes to produce the same workability as concrete with no fly ash.
4. Use of fly ash increases the demand for air-entraining admixtures up to 2-3 times that of control mix to produce an air content of around 6%.
5. Early strength of fly ash concrete is lower than that of control mix, but the strength steadily increases to reach values similar to that of control mix. Superplasticizers impart high strength to the fly ash mixes, while excess air content in the mix (8%) tends to reduce the strength.
6. Adequate resistance to freeze and thaw can be attained for fly ash concrete mixes that have an air content in excess of 5%.
7. The following fly ash concrete mixes had 28 day strengths within the required

range of 45 - 60 MPa and also possessed high workability and adequate durability:

- Mix 74: 50% Forestburg replacing cement (Type I)
- Mix 77: 50% Sundance replacing cement (Type III)
- Mix 79: 40% Sundance replacing cement (Type I)
- Mix 82: 40% Wabamun replacing cement (Type I)
- Mix 81: 50% Sundance replacing cement (Type I)

Table 5.7 gives the mix proportions for the above mixes.

8. The mixes mentioned in 7 may be applied in the construction of structural elements such as slabs, beams, columns, and foundations that require high strength. These mixes will have the following advantages over conventional concrete mixes with no fly ash;
    - reduced material cost,
    - higher durability,
    - lower permeability,
    - lower drying shrinkage,
    - lower temperature rise during hydration making the concrete less susceptible to shrinkage cracks.
9. The following fly ash concrete mixes had 28 day strengths between 35 and 45 MPa and also possessed high workability and adequate durability.

Mix 71: 60% Sundance fly ash replacing cement (Type I)
Mix 73: 60% Wabamun fly ash replacing cement (Type I)
Mix 75: 60% Forestburg fly ash replacing cement (Type I)
Mix 80: 40% Forestburg fly ash replacing cement (Type I)

The mix proportions for the above mixes are given in Table 5.7. These mixes can be used in the construction of structural elements such as floor slabs, walls in basements, etc., and in curb and gutter construction and roadways. Use of these high fly ash mixes will have similar benefits as mentioned in 8 over conventional concrete mixes.

10. Replacement of normal portland cement (Type I) by high early strength cement (Type III) yields mixes with higher strength, particularly when the mix contains fly ash.

In general, high fly ash concrete with chemical admixtures may be designed to be as strong and durable as regular high strength concrete. The conclusions that are drawn from the results of this study can be considered true only for the Alberta fly ashes and mix proportions investigated; they should not be applied universally to other fly ashes of similar origins without similar testing.

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APPENDIX "A"

Results of Trial Mixes

Table A. Results of Trial Mixes

Mix	Cement (kg/m^3)	Fly Ash (kg/m^3)	C.Agg (kg/m^3)	F.Agg (kg/m^3)	W/C	AEA (ml)	S.P. (ml)	Density (kg/m^3)	Slump (mm)	Air content (%)	7-day Strength (MPa)	28-day Strength (MPa)
1	150	150 (SD)	1100	800	.32	95	400	2181	10	5.5	15.2	28.7
2	150	150 (SD)	1100	800	.31	125	1200	****	7	4.5	18.2	30.0
3	150	150 (SD)	1012	712	.31	150	1200	****	105	3.8	22.4	39.8
4	233	233 (SD)	1035	652	.32	200	1200	****	250	14.5	12.3	21.7
5	233	233 (SD)	1035	652	.32	120	400	****	130	2.8	21.4	37.4
11	260	260 (SD)	1088	700	.28	170	900	2269	170	5.4	23.1	41.5
12	260	260 (SD)	1144	643	.31	175	600	2273	180	5.4	21.7	39.1
13	260	260 (SD)	1037	751	.28	180	700	2110	230	14.5	12.1	20.2
14	233	233 (SD)	1088	700	.28	180	800	2266	220	6.0	28.5	45.6
15	190	190 (SD)	1088	700	.28	180	1000	2351	180	4.0	27.1	43.9
16	233	233 (SD)	1088	700	.27	190	800	2351	130	3.5	31.7	42.1
17	233	233 (SD)	1088	700	.34	170	400	2252	195	7.0	18.9	31.4
27	233	233 (SD)	1144	643	.28	270	700	2351	100	4.2	22.2	33.2

*** No data available.

Table A. (Cont'd)

Mix	Cement (kg/m^3)	Fly Ash (kg/m^3)	C.Agg. (kg/m^3)	F.Agg. (kg/m^3)	C/W	AEA (ml)	S.P. (ml)	Density (kg/m^3)	Slump (mm)	Air Content (%)	7-day Strength (MPa)	28-day Strength (MPa)
29	233	233 (SD)	1037	751	.27	340	900	2351	170	4.6	26.9	38.2
42	233	233 (SD)	1088	700	.29	250	600	2337	130	5.4	17.6	35.5
43	186	280 (SD)	1088	700	.29	250	400	2238	150	8.0	15.1	27.9
51	233	233 (SD)	1088	700	.28	250	1000	2188	75	5.5	23.3	42.1
60	165	165 (SD)	1100	800	.28	80	2424	2228	20	10.0	9.6	****
61	233	233 (SD)	1088	700	.28	150	1200	2215	220	5.8	22.1	40.6
62	233	233 (SD)	1088	700	.28	180	1000	2282	170	4.8	24.3	40.2
63	280	186 (SD)	1088	700	.28	180	1020	2255	170	6.5	29.1	42.1
69	233	233 (SD)	1088	700	.28	170	800	2215	220	10.1	21.4	31.3
70	233	233 (SD)	1088	700	.28	130	562	2268	100	4.8	26.3	34.2
6	233	233 (WB)	1035	652	.32	150	400	****	15	4.3	20.3	34.8
7	233	233 (WB)	1088	666	.32	170	900	2252	180	6.6	22.3	37.1
8	233	233 (WB)	1088	666	.32	170	600	2177	14	3.1	19.8	30.8
9	233	233 (WB)	1088	666	.29	200	1200	2316	220	4.8	26.0	40.0
10	260	260 (WB)	1088	700	.30	170	1200	2337	220	3.9	26.2	41.7

Table A. (Cont'd)

Mix	Cement (kg/m^3)	Fly Ash (kg/m^3)	C.Agg. (kg/m^3)	F.Agg. (kg/m^3)	W/C	AEA (ml)	S.P. (ml)	Density (kg/m^3)	Slump (mm)	Air Content (%)	7-day Strength (MPa)	28-day Strength (MPa)
34	233	233 (WB)	1088	700	.29	300	700	2337	80	5.0	21.5	33.3
35	233	233 (WB)	1088	700	.30	300	700	2323	85	5.5	20.5	34.8
40	190	190 (WB)	1088	700	.29	320	1600	2323	70	4.5	15.4	23.8
41	233	233 (WB)	1198	590	.29	320	770	2309	100	6.3	19.2	31.2
44	233	233 (WB)	1088	666	.29	300	800	2309	200	4.5	21.9	35.2
45	233	233 (WB)	1088	666	.29	300	720	2295	100	7.0	19.2	35.1
50	233	233 (WB)	1088	700	.28	340	1200	2188	40	3.0	22.0	43.4
52	186	280 (WB)	1088	700	.28	350	1400	2322	60	3.0	21.4	35.5
55	280	186 (WB)	1088	700	.29	300	1150	2336	45	3.0	26.6	40.3
56	233	233 (WB)	1088	700	.28	180	1400	2254	45	2.0	26.1	51.8
58	233	233 (WB)	1088	700	.28	180	1095	2322	180	1.4	18.4	30.5
59	233	233 (WB)	1088	700	.29	180	900	2342	90	2.4	23.9	42.5
64	233	233 (WB)	1088	700	.30	190	640	2362	90	1.7	23.0	43.1
65	280	186 (WB)	1088	700	.29	200	1200	2295	220	3.4	19.3	24.3
18	233	233 (FB)	1088	700	.29	180	800	2252	235	4.0	18.0	27.2

Table A. (Cont'd)

Mix	Cement (kg/m^3)	Fly Ash (kg/m^3)	C.Agg. (kg/m^3)	F.Agg. (kg/m^3)	W/C	AEA (ml)	S.P. (ml)	Density (kg/m^3)	Slump (mm)	Air Content (%)	7-day Strength (MPa)	28-day Strength (MPa)
19	233	233 (FB)	1088	700	.27	190	890	2323	240	3.5	18.5	26.0
20	233	233 (FB)	1144	643	.27	200	814	2351	220	2.8	21.3	31.7
21	233	233 (FB)	1037	751	.27	200	1050	2365	180	3.5	25.7	34.9
22	260	260 (FB)	1088	700	.27	200	900	2323	180	2.8	17.7	23.4
23	233	233 (FB)	1088	700	.34	200	600	2224	140	6.3	12.9	25.2
24	260	260 (FB)	1088	700	.27	220	1200	2337	220	3.0	13.2	17.7
25	190	190 (FB)	1088	700	.26	240	1250	2351	175	3.5	18.0	26.8
26	233	233 (FB)	1198	590	.28	320	700	2266	180	5.5	21.3	30.3
28	233	233 (FB)	1088	700	.27	320	1100	2365	200	3.1	24.6	31.3
30	233	233 (FB)	1088	700	.27	380	1000	2337	170	5.0	23.4	29.8
31	233	233 (FB)	1037	751	.27	400	1200	2351	200	3.2	20.2	26.7
32	233	233 (FB)	1037	751	.29	300	750	2252	110	7.0	18.8	29.7
33	233	233 (FB)	1037	751	.30	280	700	2210	100	7.6	17.2	29.1
47	233	233 (FB)	1088	700	.29	280	1080	2210	220	8.5	14.0	23.5
48	233	233 (FB)	1088	700	.28	320	900	2245	50	4.8	21.6	30.8

Table A. (Cont'd)

Mix	Cement (kg/m³)	Fly Ash (kg/m³)	C.Agg. (kg/m³)	F.Agg. (kg/m³)	W/C	AEA (ml)	S.P. (ml)	Density (kg/m³)	Slump (mm)	Air Content (%)	7-day Strength (MPa)	28-day Strength (MPa)
49	233	233 (FB)	1088	700	.28	350	1257	2154	50	7.4	18.4	32.2
53	186	280 (FB)	1088	700	.28	320	1400	2174	170	7.6	12.7	22.7
54	280	186 (FB)	1088	700	.29	300	1400	2161	210	9.0	17.4	28.2
57	233	233 (FB)	1088	700	.28	180	1300	2228	220	4.6	11.9	****
66	233	233 (FB)	1088	700	.28	190	1300	2188	210	7.4	15.5	29.1
67	233	233 (FB)	1088	700	.28	190	2485	2201	200	5.3	5.3	****
68	280	186 (FB)	1088	700	.28	170	1300	2242	200	5.6	22.3	33.8
36	380	0	1088	700	.34	180	1000	2224	100	12.0	28.4	33.7
37	466	0	1088	700	.32	0	1100	2465	220	1.6	36.1	41.3
38	380	0	1088	700	.34	100	950	2337	170	7.7	30.0	37.1
39	466	0	1088	700	.34	100	580	2394	70	4.8	31.1	37.4
46	466	0	1088	700	.32	100	800	2436	110	3.5	37.5	43.4

AEA = Air Entraining Agent, S.P. = Superplasticizer, C.Agg. = Coarse Aggregate

F.Agg. = Fine Aggregate, SD = Sundance, WB = Wabamun, FB = Forestburg.

APPENDIX "B"

Initial and Final Setting Times for Fly Ash Cement Paste

APPENDIX "C"

Cost of Raw Materials

APPENDIX C

Table C. Cost of raw materials used for final mix designs for different locations in Alberta.

Material	LOCATION			
	Edmonton	Calgary	Lethbridge	Peace River
Sundance ($/tonne)	43	58	68	67
Forestburg ($/tonne)	40	50	70	75
Wabamun ($/tonne)	36	51	61	60
Cement ($/tonne)	133	129	126	163
Coarse Aggregate ($/m^3)	25	25	25	25
Fine Aggregate ($/m^3)	30	30	30	30
Superplasticizer ($/lit)	3.05	3.05	3.05	3.05
Air-entraining adm. ($/lit)	1.9	1.9	1.9	1.9

Sample Calculation

Mix 79 (Edmonton):

$$\text{Cost} = \underset{\underline{\textit{Fly Ash}}}{186\ (\text{kg/m}^3) \times \$\ 43/1000\ \text{kg}} + \underset{\underline{\textit{Cement}}}{280\ (\text{kg/m}^3) \times \$\ 133/1000\ \text{kg}} + \underset{\underline{\textit{Coarse Aggregate}}}{0.41\ \text{m}^3 \times \$\ 25/\text{m}^3} + \underset{\underline{\textit{Fine Aggregate}}}{0.25\ \text{m}^3 \times \$\ 30/\text{m}^3}\ +$$

$$\underset{\underline{\textit{Air Entraining Adm.}}}{130\ \text{ml} \times \$1.9/1000\ \text{ml}} + \underset{\underline{\textit{Superplasticizer}}}{1125\ \text{ml} \times \$\ 3.05/1000\ \text{ml}} = \underset{\underline{\textit{Cost of Concrete Mix per cubic meter}}}{\$\ 66.6/\text{m}^3}\ \text{(see Table 5.10).}$$